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EMPIRICAL METHODS FOR FORECASTING THE MAXIMUM STORM TIDE DUE TO HURRICANES AND OTHER TROPICAL STORMS

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1. INTRODUCTION

Of all the causes of death and destruction from tropical storms the most treacherous is the rise in sea level associated with the landfall of the storm, a phenomenon known as the storm surge. This is true because the rise in sea level along the coast in flat regions may lead to the penetration of the sea 10 to 20 miles inland. Not only are regions near the coast flooded by the intrusion of salt water, but erosion processes due primarily to wave action are effective inland far beyond the normal coastline. Occasionally, significant breaks in barrier reefs are produced by the combination of erosion due to wave damage and the storm surge.

Another factor in the insidious behavior of the storm surge is that the surge generated on the open coast must move inland as a gravity wave, and thus the peak disturbance at the end of a long channel, such as Long Island Sound, may occur many hours after the other signs of hurricane fury have begun to diminish. Interaction with the astronomical tide also may cause the most severe flooding to occur several hours before or after the peak intensity of the storm.

The extent of coastal flooding produced by hurricanes along the open coast depends on the wind field, the pressure deficiency, the size and speed of motion of the storm, the bottom topography near the landfall of the storm, and the astronomical tide (Harris [4] and Reid and Wilson [9]). The disturbance generated in open water is further modified by convergence or divergence of the surge and local wind setup, seiching, and perhaps rainfall runoff in the mouths of rivers and other estuaries.

The forecast centers do not have the facilities required for a full consideration of all these factors in the time available for a forecast during a hurricane threat. Accordingly it has been necessary to seek some empirical procedure which combines a number of these effects into a single parameter to give an estimation of the extreme tide to be expected with any hurricane.

2. DERIVATION OF EQUATIONS

Since the data from a large number of storms must be combined, and detailed data concerning the structure of a storm are rarely available before the storm moves inland, only a simple storm model can be used. The simplest model which appears reasonable is one in which the pressure depends only on the distance from the center of the storm. With such a storm, the maximum wind speed depends on the pressure deficiency. Near the center of the storm the cyclostrophic effect greatly exceeds the geostrophic and the maximum wind speed (V_{max}) can be taken as

$$V_{max}=K(p_n-p_0)^{1/2} \tag{1}$$

where p_n is the pressure at the edge of the storm; p_0 is the pressure at the center of the storm, and K is a constant of proportionality. Equation (1) has been given by Myers [7], Fletcher [3], and others. A study of the maximum wind speeds in Gulf of Mexico hurricanes, made

at the New Orleans Forecast Center [2] several years ago, showed that the results obtained by holding p_n constant at 1005 mb. were not significantly inferior to the results obtained by using a variable p_n. For several years the equation

$$V_{max}=75\sqrt{(1005-p_0)/12} \text{ for } (1005-p_0)>12 \qquad (2)$$

where V_{max} is given in miles per hour and p_0 in millibars, has been used by the New Orleans Forecast Center [2] to estimate the extreme wind speed to be expected in a hurricane. Equations of similar form have been found empirically by Takahashi [10] and others for typhoon winds.

The setup due to wind should be proportional to the wind stress. According to many writers the wind stress, τ, should be given by

$$\tau=\rho\gamma^2V^2 \qquad (3)$$

where ρ is density of the air, γ^2 is the wind stress coefficient, depending on the surface roughness, and V is the wind speed. Neumann [8], noting that the surface roughness over water depends on the wave height, which in turn depends on the wind speed, prefers an expression of the form

$$\tau=\rho AV^{3/2} \qquad (4)$$

where A is a constant. Others writer (Montgomery [6]) have preferred other values for the exponent of V and have given the total setup h in the form

$$h=BV^{2b} \qquad (5)$$

where B and b are constants to be determined from the data. Combining (1) and (5), we obtain,

$$h=B(p_n-p_0)^b \qquad (6)$$

Equations (1) and (3), when combined with equation (6), imply that $b=1$. In this case we can write (6) in the more usual form for regression equations:

$$h=a+b'p_0 \qquad (7)$$

Equations (1) and (4), when combined with (6), imply that $b=3/4$. Reid and Wilson [9], working with a very simple hurricane model, found that with a continental shelf of constant slope, b could equal 3/4 even with equation (3). Their results depended on their assumed model hurricane, slope of the continental shelf, and wind stress law. This implies that in a purely empirical study such as this, one might expect to obtain better results by assuming that B and b are both arbitrary constants to be determined from the data. This can be accomplished most simply by taking the logarithm of both sides of equation (6) to obtain

$$\log h = \log B + b \log (p_n - p_0). \qquad (8)$$

This is of the form $y = a + bx$, and a and b can be obtained by the method of least squares.

3. APPLICATION TO GULF HURRICANE DATA

The logic of this derivation shows that it should be expected to apply to the storm surge; that is, to the difference between the observed storm tide and the astronomical tide. Also it should apply only to the maximum tide on the open coast uninfluenced by convergence or oscillations in bays. The exact time of the peak surge on the open coast is generally unknown, even when the maximum water level is known, so that corrections for the astronomical tide are often impossible when dealing with the records of past storms. However, the range of tide in the Gulf of Mexico is generally small, usually less than one foot, and the observed departure from mean sea level provides a useful approximation to the storm surge during exceptionally high tides.

The selection of the particular report which best represents the extreme tide height on the open coast, with a minimum of local influences due to estuarian effects, is somewhat subjective, and no two workers will agree completely on all cases. Nevertheless, reasonably satisfactory data have been found for 30 hurricanes entering the United States from the Gulf of Mexico prior to 1956. Some of these data were obtained from Cline [1] and Hubert and Clark [5]. Many were obtained from hurricane survey reports now being prepared by the U. S. Army Corps of Engineers. Others were obtained from hurricane descriptions in early editions of the *Monthly Weather Review* or from Coast and Geodetic Survey records.

These data are listed in table 1 and plotted in figure 1 as a function of the central pressure of the storm as it crossed the coast. The central pressures were taken from table 3-1, U. S. Weather Bureau [12] except where otherwise noted. No reliable reports of the maximum water levels were obtained for storms with lowest pressure below 934 mb. The "Labor Day" hurricane of 1935 had a reliably reported minimum pressure of 892 mb., the lowest sea level pressure reported in the United States, and was attended by a storm wave whose height has been estimated at 15 to 20 ft. above mean low water (Tannehill [11]). This value has been adjusted to mean sea level and is plotted as a range in figure 1, as this is the best available data for extending the range of the prediction curve.

If the data in table 1 are analyzed according to equation (6) and p_n is taken as 1005 mb. as in equation (2), the resulting equation* is

$$h_{max}=0.867(1005-p_0)^{0.618} \qquad (9)$$

*An empirical system similar to that described in this paper has been used at the Weather Bureau Forecast Center in New Orleans for several years. With the data first obtained [2], this equation took the form

$$h_{max}=\tfrac{3}{4}(1005-p_0)^{2/3}$$

The maximum storm tide in hurricane Flossy of 1956 was successfully forecast by this equation.

TABLE 1.—*Lowest central pressure and highest tides of Gulf of Mexico hurricanes.*

	Date	Location of highest tide on open coast	Lowest pressure (mb.)	Maximum tide height (feet)
1	Oct. 2, 1893	Mobile, Ala.	956	8.4 m. s. l.
2	Sept. 8, 1900	Galveston, Tex.	936	14.5 m. s. l.
3	Aug. 14, 1901	Mobile, Ala.	973	7.4 m. s. l.
4	Sept. 27, 1906	Fort Barrancas, Fla.	965	10.8 m. s. l.
5	July 21, 1909	Galveston, Tex.	959	10.0 m. s. l.
6	Sept. 20, 1909	Mobile, Ala.	980	7.8 m. s. l.
7	Sept. 13, 1912	Mobile, Ala.	*993	4.4 m. s. l.
8	Aug. 16, 1915	High Island, Tex.	953	13.9 m. s. l.
9	Sept. 29, 1915	Grande Isle, La.	944	9.0 m. s. l.
10	July 5, 1916	Fort Morgan, Ala.	961	4.7 m. s. l.
11	Sept. 28, 1917	Fort Barrancas, Fla.	964	7.1 m. s. l.
12	Sept. 14, 1919	Port Aransas, Tex.	948	11.1 m. s. l.
13	Oct. 25, 1921	St. Petersburg, Fla.	958	7.8 m. s. l.
14	Aug. 25, 1926	Timbalier Bay, La.	959	10.0 m. s. l.
15	Sept. 20, 1926	Pensacola, Fla.	955	7.6 Ab. Nor.
16	Sept. 5, 1933	Brownsville, Tex.	949	13.0 m. s. l.
17	July 25, 1934	Galveston, Tex.	**975	5.9 m. s. l.
18	July 31, 1936	Panama City, Fla.	964	6.0 m. s. l.
19	Aug. 7, 1940	Calcasieu Pass, La.	974	4.8 m. s. l.
20	Sept. 23, 1941	Sargent, Tex.	959	9.9 m. s. l.
21	Oct. 7, 1941	St. Marks, Fla.	981	8.0 m. s. l.
22	Aug. 30, 1942	Matagorda, Tex.	951	14.8 m. s. l.
23	July 27, 1943	Galveston, Tex.	975	4.0 m. s. l.
24	Aug. 27, 1945	Matagorda, Tex.	968	7.3 Ab. Nor.
25	Aug. 24, 1947	Sabine Pass, La.	*992	3.6 m. s. l.
26	Sept. 19, 1947	Biloxi, Miss.	968	11.1 m. s. l.
27	Sept. 4, 1948	Biloxi, Miss.	*987	5.6 m. s. l.
28	Oct. 4, 1949	Freeport, Tex.	978	10.4 Ab. Nor.
29	Aug. 30, 1950	Pensacola, Fla.	979	5.5 m. s. l.
30	Sept. 5, 1950	Cedar Key, Fla.	*958	5.1 Ab. Nor.

* Pressure data from *Monthly Weather Review*.
**An observed pressure of 986 mb. is reported in *Monthly Weather Review*. Data on file in the New Orleans Weather Bureau Office indicate that the central pressure was at least as low as 975 mb.

with a correlation coefficient of 0.66. If the data are analyzed according to equation (7), the resulting equation is

$$h_{max}=0.154\ (1019-p_0), \qquad (10)$$

with a correlation coefficient of 0.68. Both curves are plotted on figure 1.

By comparing equations (9) and (10) with (6), it is seen that b is increased and B is decreased as p_n is increased from 1005 to 1019 mb. The correlation coefficient with the dependent data does not change significantly within this range of B, b, and p_n. (See Weatherburn [13], pp. 200–202, for a method of testing significance of correlation coefficients.)

A slightly higher correlation coefficient could have been obtained by using a much higher value of p_n and an exponent greater than 1.0 in equation (6). This, however, would be contrary to physical reasoning. As the storm tide rises to ever greater heights, the area over which the water can spread increases and the volume of water needed to produce a given rise in tide is greatly increased. It is evident that the curve which describes the relationship between the intensity of the storm and the height of the storm surge must ultimately curve downward toward the right. Although the reported tide height for the 1935 Labor Day storm suggests that this bending to the right occurs for storms with a central pressure slightly higher than 900 mb., the records from this storm are somewhat uncertain and it is not clear from the data presented here that this is the case. On the basis of the evidence presented in this paper, the straight line relationship appears to be the most reliable.

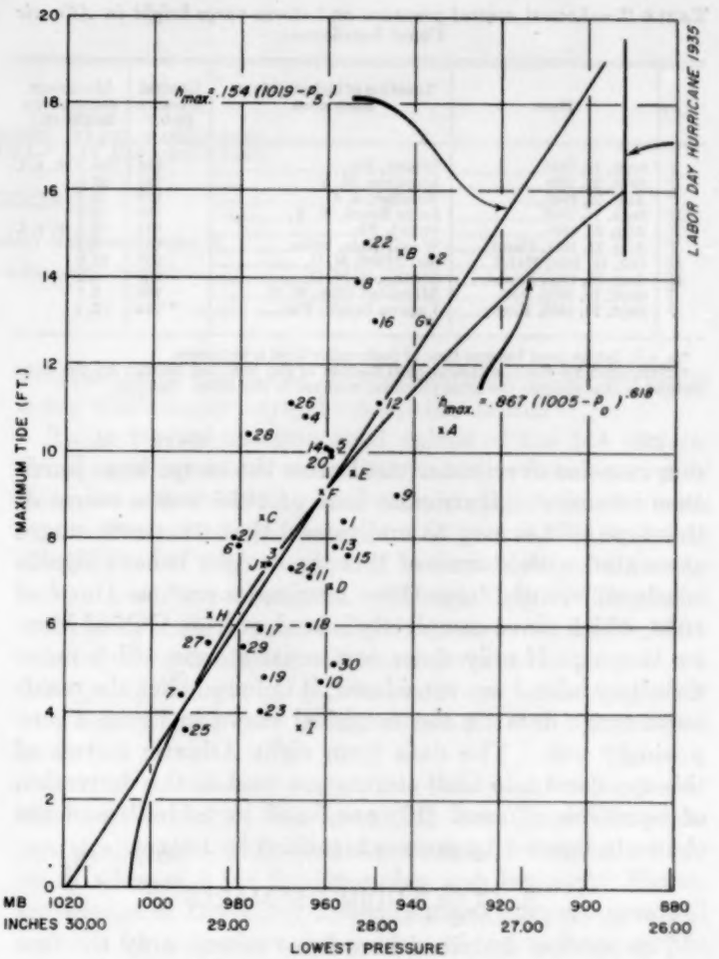

FIGURE 1.—Maximum tide or storm surge height on the open coast as a function of the central pressure. Dependent data are plotted as points and are identified with the data in table 1 by Arabic numerals. Independent data are plotted as crosses and identified with the data in table 2 by letters. The reports of the storm tide associated with the "Labor Day" hurricane of 1935 are somewhat indefinite as 15.0 to 20.0 ft. mean low water. This is shown as a range above mean sea level, as this hurricane had the lowest central pressure observed in the United States.

4. TEST ON ATLANTIC HURRICANE DATA

The tide range along the Atlantic Coast of the United States is much greater than in the Gulf and it is necessary to consider the difference between the observed and predicted tides, at the time of the maximum difference, in order to obtain reasonable homogeneity of the data when plotting a graph such as figure 1. When the difference is considered, many of the available points for the east coast fall near the line on figure 1. Most of the others fall well below the line.

The reason for this is not very difficult to find. Hurricanes which enter the Gulf of Mexico must come completely inland to escape from the Gulf. However, many of those which move up the east coast skirt the coastline and, even though the center or lowest pressure may be over land for a period of time, much of the storm circula-

TABLE 2.—*Lowest central pressure and storm surge height in Atlantic Coast hurricanes*

	Date	Location of highest tide on open coast	Central pressure (mb.)	Maximum storm surge height (ft.)
A	Sept. 18, 1926	Miami, Fla.	934	*10.5 m. s. l.
B	Sept. 21, 1938	Moriches, N. Y.	943	14.6
C	Aug. 11, 1940	Beaufort, S. C.	975	8.5
D	Sept. 14, 1944	Jones Beach, N. Y.	959	6.9
E	Aug. 26, 1949	Stuart, Fla.	954	*9.5 m. s. l.
F	Aug. 31, 1954, Carol	Woods Hole, Mass.	961	9.1
G	Oct. 15, 1954, Hazel	Southport, N. C.	937	13.0
H	Aug. 17, 1955, Diane	Southport, N. C.	987	6.2
I	Sept. 19, 1955, Ione	Morehead City, N. C.	966	3.6
J	Sept. 24, 1956, Flossy	Laguna Beach, Fla.	**974	7.4

*m. s. l. datum used because time of peak water level is unknown.
**Computed by Hydrometeorological Section of the Weather Bureau by the same method as that used for the other pressures reported in this table. See [12].

tion remains over water until after the storm loses hurricane intensity. Hurricane Ione of 1955 was a storm of this type. It is easy to understand that the storm surges associated with storms of this type might behave significantly differently from those hurricanes such as Hazel of 1954, which move completely inland, or from Gulf of Mexico storms. If only those east coast storms which move definitely inland are considered, it is found that the maximum surge data fit the empirical curve in figure 1 surprisingly well. The data from eight Atlantic storms of this type and two Gulf storms not used in the derivation of equations (9) and (10) are listed in table 2, and are shown in figure 1 by crosses identified by letters.

5. CONCLUDING REMARKS

The method described here is, of course, only the first step in the development of a storm surge forecasting system for hurricanes. It is worth noting, however, that this single meteorological parameter, central pressure, can account for approximately half of the total variability of the storm surge height on the open coast. The other meteorological parameters which could be easily considered in this way, the asymptotic pressure, the radius of maximum winds, the forward speed of the storm, and the angle with which the storm crosses the coast, when considered alone, do not make a significant improvement to the prediction equation. This is not because these parameters are unimportant, but because their effects are combined with those of local topography in such a way that their influence cannot be properly described by the methods used in this paper.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the several district offices of the Corps of Engineers and to the Coast and Geodetic Survey for supplying most of the unpublished storm tide data used in this paper.

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SUNSPOTS AND WEATHER

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The possibility that sunspots affect weather, and might be made a basis for long-range forecasting, has been recognized for many years, and their effect on "radio weather" is well known. Recently there seems to be renewed interest in this matter, and it is sometimes said that the subject has become "respectable" among meteorologists. The purpose of this note is to point to evidence that *no* phenomenon having a period in the vicinity of 10 years has any great effect on weather for at least some weather elements in some places. A single example will be given.

Norton and Brier [1] studied persistence in Greenwich monthly mean temperatures. One hundred years of data, 1764 to 1863, were used and the correlation between months was computed for each interval from one to twelve months inclusive, separately for each of the twelve possible antecedent (or subsequent) months. The 144 correlations, each based on 99 pairs of observations, of which the antecedent fell in the years 1764 to 1862 inclusive, were taken as data for statistical analysis. In brief, it was found that the correlation decreased curvilinearly with increasing interval, as would be expected a priori, falling from an average of about 0.3 for consecutive months to about half that for months one year apart, and that there was an annual cyclic variation in each of the twelve intervals studied. These twelve cycles were in phase with respect to the subsequent (but not the antecedent) month of the pair, which could be adequately represented by an annual sine wave plus the first harmonic (that is, a wave of period 6 months), amounting to deviations from the average correlation for a given interval of about 0.10 when August or September was the subsequent month, and −0.14 for January, both the decrease with increasing interval and the cyclic variation being statistically beyond reasonable doubt.

Table 1 gives the smoothed values of the 144 correlations, that is, values estimated from the fitted curves of decrease with increasing interval and cyclic variation with the twelve subsequent months. Of course, the sampling reliability of these smoothed values does not justify retention of three decimals. Though they are improved compared to the unsmoothed correlations, which were subject to a sampling standard error averaging about 0.099, they are yet subject to an average sampling error of about 0.0194 (not 0.088 as stated by Norton and Brier [1]).

It is of particular interest, in connection with possible effects of sunspots, that many of these correlations are practically zero, and even for consecutive months they reach a low of 0.158 for December and January. Hence, knowledge of December monthly mean temperatures will account for only about 2.5 percent of the variation in the immediately succeeding January mean temperatures. Even if it were supposed that the estimated correlation of 0.158 was seriously too low as the result of sampling errors, its 1 percent upper confidence limit is only 0.214. It follows that there is less than one chance in a hundred that the December monthly mean temperature at Greenwich accounts for as much as 4.6 percent of the variance of the immediately subsequent January mean temperature.

To make such correlations bear upon the possibility of a relation between sunspots and weather it is only necessary to recognize that the sunspot cycle extends over several years and that its effect upon terrestrial weather must result in a correlation between observations which are

TABLE 1.—*Smoothed correlations*

Antecedent month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
January	0.004	0.174	0.193	0.221	0.236	0.238	0.241	0.245	0.234	0.187	0.109	0.034
February	−.007	.020	.232	.255	.265	.262	.260	.259	.243	.191	.108	.028
March	−.013	.009	.077	.294	.299	.291	.284	.278	.257	.200	.112	.027
April	−.014	.004	.066	.139	.338	.325	.313	.302	.276	.214	.121	.032
May	−.010	.003	.060	.128	.183	.364	.347	.331	.300	.233	.135	.041
June	−.001	.007	.060	.123	.172	.209	.385	.365	.328	.257	.154	.055
July	.013	.016	.064	.122	.166	.199	.231	.404	.362	.286	.178	.074
August	.032	.030	.073	.126	.166	.193	.220	.249	.401	.320	.207	.098
September	.056	.049	.087	.135	.170	.192	.214	.238	.247	.358	.241	.126
October	.085	.073	.106	.149	.179	.196	.214	.233	.236	.304	.280	.160
November	.119	.102	.130	.168	.193	.205	.218	.232	.230	.193	.125	.199
December	.158	.136	.159	.192	.212	.219	.227	.236	.229	.188	.114	.045

separated by a few months or less. In particular, if the sunspot cycle imposed on terrestrial temperatures any such effect as is sometimes supposed, namely that higher sunspot numbers mean higher terrestrial temperatures, the effect upon any December and the immediately following January would be nearly the same because one month is so small a part of the sunspot cycle, which averages about 11 years.

In fact, to the extent that deviations of these monthly temperatures from their respective long-time means or trends were due to the effect of any cause which changes slowly through a cycle lasting roughly 10 years, (or longer up to at least a hundred years, thus including the double sunspot cycle), these deviations would be almost perfectly correlated. For example, the 1-month lag correlation for a quantity which follows a sine wave with an 11-year period is 0.99887. For a function which increases linearly through 11 years and then returns instantaneously to its original value, the 1-month lag correlation is 0.95523. This makes it plain that the failure to find a substantial correlation of December with January reflecting some cyclic cause with a period of roughly 10 years is not appreciably due to the length of the interval (1 month) between data.

It follows, that at the 1 percent confidence level, *no* such cause accounted for as much as 5 percent of the variance of January mean temperatures at Greenwich during the 99 years 1765 to 1863 inclusive. Meteorologists who find themselves thinking seriously of sunspots as an important cause of terrestrial weather will be well advised to bear this correlation in mind, and to try to develop a hypothesis of sunspot influence sufficiently detailed to include little or no influence on some important weather elements at some locations, before they spend more effort on direct search for sunspot-weather relationships.

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CORRECTION

Vol. 85, No. 1, p. 26, table 1: The temperature of −55° F. listed for Boonville, N. Y. was not officially accepted.

CORRESPONDENCE

A SIMPLIFIED EQUATION FOR MINIMUM TEMPERATURE PREDICTION

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February 25 and April 14, 1957

An invaluable aid in the quantitative prediction of radiation frost is an equation which expresses the minimum temperature as a function of the evening surface hygrometric data. Many such equations have been developed empirically for application to the source region of the original data (c. f. [1, 2]). Because the net loss of heat from the ground at night depends on complex radiation and heat conduction processes (c. f. [3, 4]), the weakness of any empirical equation based on surface data is the assumption of average values of several physical parameters which are lumped together as coefficients in the empirical equation. In certain climatic zones, however, particularly in the low-level valleys of California, this has proved to be a valid assumption. The purpose of this note is to add a very simple formula to the large family of empirical formulas that have been published previously in the *Review* (e. g., [1, 2, 5, 6]).

The formula devised by Young [7] has been adapted for use in the orange belt of the southern San Joaquin Valley of California [6]; in the majority of cases the indicated minimum is in error by less than ±3° F. The formula as currently used is as follows:

$$T_m=D-\left(\frac{H-30}{4}\right)+v+v' \tag{1}$$

where T_m is the indicated minimum temperature (° F.)
D is dewpoint (° F.) at 4:45 p. m. PST
H is relative humidity (percent) at 4:45 p. m. PST
v and v' are variable corrections that are functions of D and H, respectively. These functions, to an approximation that is within the error mentioned, are linear equations:

$$v=-\left(\frac{D-28}{3}\right) \text{ and } v'=\frac{H-52}{6} \tag{2}$$

Substitution of (2) into (1) simplifies the prediction formula to:

$$T_m=\frac{2D}{3}+\frac{98-H}{12} \tag{3}$$

Although this formula is a useful simplification of equation (1), its application with the directly observed variables, dry-bulb temperature T_d and wet-bulb temperature T_w, requires the use of psychrometric tables to obtain D and H. Thus, further simplification would result if the prediction formula was expressed directly as a function of T_d and T_w. Such a prediction formula of the following form was indeed proposed long ago by Ångström [8]:

$$T_m=a(T_w-k)-bT_d \tag{4}$$

where a, k, and b are constants to be determined empirically. Ångström found $a\approx 1$ and b to be so small that the last term could be dropped; thus his prediction formula reduced to

$$T_m=T_w-k \tag{5}$$

As prediction formulas of the form of (5) generally have not been found to be as successful as Young's formula (c. f. [2]), it seemed desirable to attempt to derive from his formula a new formula with both T_w and T_d as independent variables. To develop such a relation, hypothetical minima T_m were calculated from Young's formula for such ranges of temperature and dewpoint as usually precede frosts in the San Joaquin Valley. Examination of the results showed that for a given value T_d, the range of T_w-T_m did not exceed 3.5° F.; thus, with small error, this difference could be taken as constant. Figure 1 shows the values of T_w-T_m from the original work sheet plotted against T_d. The straight line, which closely fits the plotted points, gives the following simplified prediction formula:

$$T_m=T_w-\frac{1}{4}(T_d+16) \tag{6}$$

This simple hygrometric equation, which was devised in 1942 and has been tested since that time in the Lindsay, Calif., and the Modesto, Calif., fruit-frost districts, gives accurate results in those areas on clear, quiet nights of winter and spring. Actual comparison with the original Young formula over the entire range of temperature and dewpoint (nights with frost only) shows an average difference in the indicated minimum of less than ±0.5° F.

The advantages of the simplified equation (6) are twofold: it is not necessary to refer to tables for dewpoint and relative humidity values, or to tables of constants—the indicated minimum can be calculated mentally and quickly when the dry and wet bulb temperatures are known;

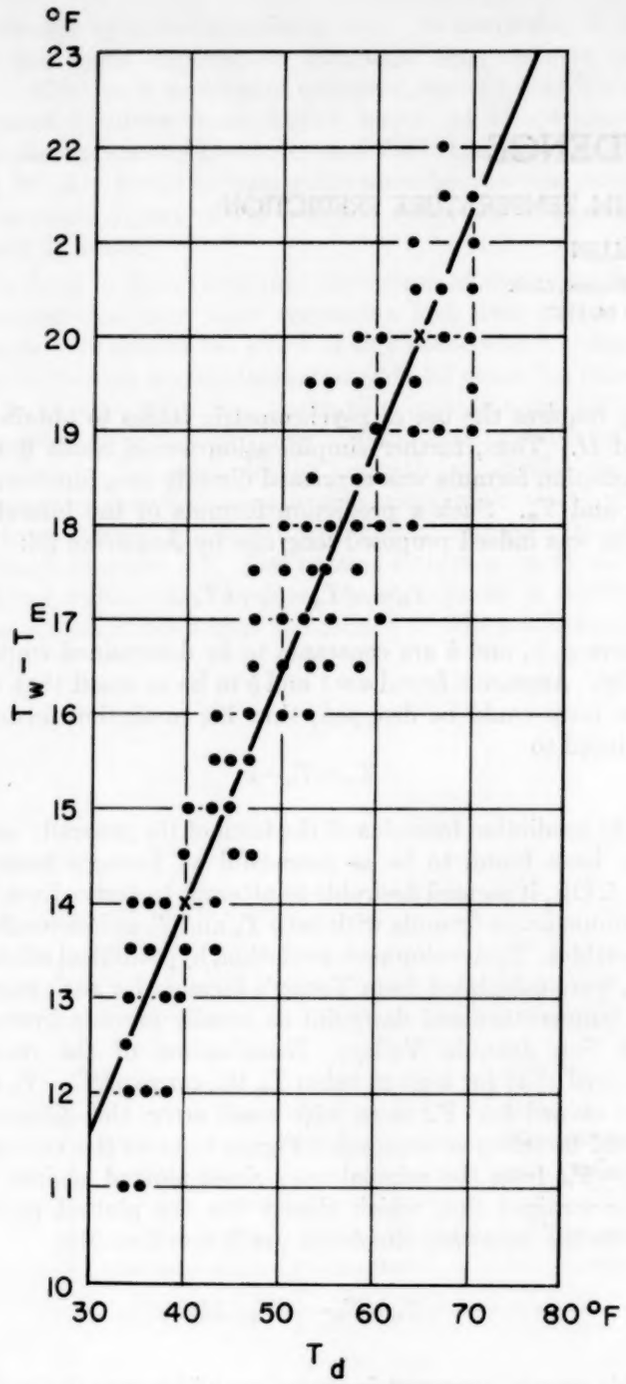

FIGURE 1.—Relation between dewpoint temperature at 4:45 p. m. PST and the difference $(T_w - T_m)$ for the San Joaquin Valley.

further, the tests in the Lindsay and Modesto districts suggest that this form of equation can easily be fitted to data for climatically similar localities by changing the slope and intercept constants. It would be of interest to plot the relation of $(T_w - T_m)$ vs. T_d in climatically different localities to test whether the linearity is of a local or universal nature.

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RELATIONSHIP OF NORMAL INCIDENCE RADIATION TO MAXIMUM VISIBILITY AT BLUE HILL OBSERVATORY

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Normal incidence radiation, that which is received on a surface at a right angle to the sun, is of interest to agriculturalists, engineers, and others. To provide an estimate of normal incidence radiation when measurements are absent, the relationship of this radiation to horizontal visibility was investigated for those times when there were no clouds in front of the sun. In this paper are presented in graphic form the average values of normal incidence radiation for the principal air masses at various maximum visibilities for each month of the year.

According to [1], air mass "is the length of the atmospheric path traversed by the sun's rays in reaching the earth, measured in terms of the length of this path when the sun is in the zenith." Maximum horizontal visibility, as observed at the Blue Hill Observatory, describes the greatest degree of transparency of the atmosphere in any direction. It is defined as the maximum distance, in miles, at which an object can be seen and the clearness with which its details can be discerned [2]. Visibility values are observed and recorded by the Blue Hill Observatory staff. Normal incidence radiation readings are taken at the Observatory by the U. S. Weather Bureau with an Eppley tube, and recorded on a Brown Electronik recorder.

Data for the years 1949 to 1956 were used in this investigation. Table 1 lists the number of observations taken for the four principal air masses for each month. The maximum number of observations occurred during August, September, and October, while the minimum occurred during the spring months of April and May. There was an average of 16 observations per month for the 8 years of record for the No. 3 air mass in September, while an average of only 9 per month for the No. 4 air mass in April. No attempt was made to draw a curve for the No. 2 air mass in November, due to the sparseness of observations (35). During December and January there were no observations taken at the No. 2 air mass because of the low solar trajectory. The observations for each of the four air masses were further subdivided according to maximum horizontal visibility and mean values of radiation for each 10-mile multiple of visibility were obtained by dividing the total value of all observations at each multiple by the number of observations. Figure 1 shows plots of these values with curves fitted to them by eye.

These curves indicate a three-dimensional characteristic:
(1) Increased values of radiation with decreased air mass.
(2) Increased values of radiation with increased visibility.
(3) Increased values of radiation from summer to winter.

1. Low air mass numbers indicate a decrease in the length of path of the radiation, and thus a reduction in the amount of radiation reflected, scattered, or absorbed by the atmosphere and atmospheric contaminants. The average radiation difference between each successive air mass, maintaining the same visibility, is about 0.13 langley per minute.

2. Visibility is a criterion of the degree of contamination (dust, haze, smoke, etc.) in the atmosphere. Maximum visibility rather than average visibility was used, as it more closely represents true air mass visibility. Pockets of local contamination (especially over the city 10 miles north) greatly affect the average visibility but have little or no effect on the maximum visibility in some other direction. There is an average difference of 0.2 to 0.3 langley per minute in the mean beam radiation intensity corresponding to the maximum visibility of 10 miles and that corresponding to 100 miles visibility.

3. A combination of several conditions accounts for the seasonal differences. For example, at perihelion (December) the intensity, due to the nearness of the earth to the sun, is roughly 7 percent greater than at aphelion (June) [3]. The amount of water vapor in the air is considerably less in winter than in summer, and therefore less radiation is absorbed, resulting in higher intensities in winter. Various months were paired to indicate the maximum variability between seasons. As indicated above, December and June along with January and July produced the greatest disparity. These differences were on the order of 0.1 to 0.3 langley per minute for comparable air masses and visibilities.

TABLE 1.—*Number of observations for each air mass for each month*

Air mass	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2		87	94	97	86	98	101	103	124	124	35	
3	89	92	104	80	80	100	98	112	130	129	89	108
4	91	98	105	70	71	88	91	110	120	127	93	104
5	93	99	96	66	66	78	85	104	111	120	87	102

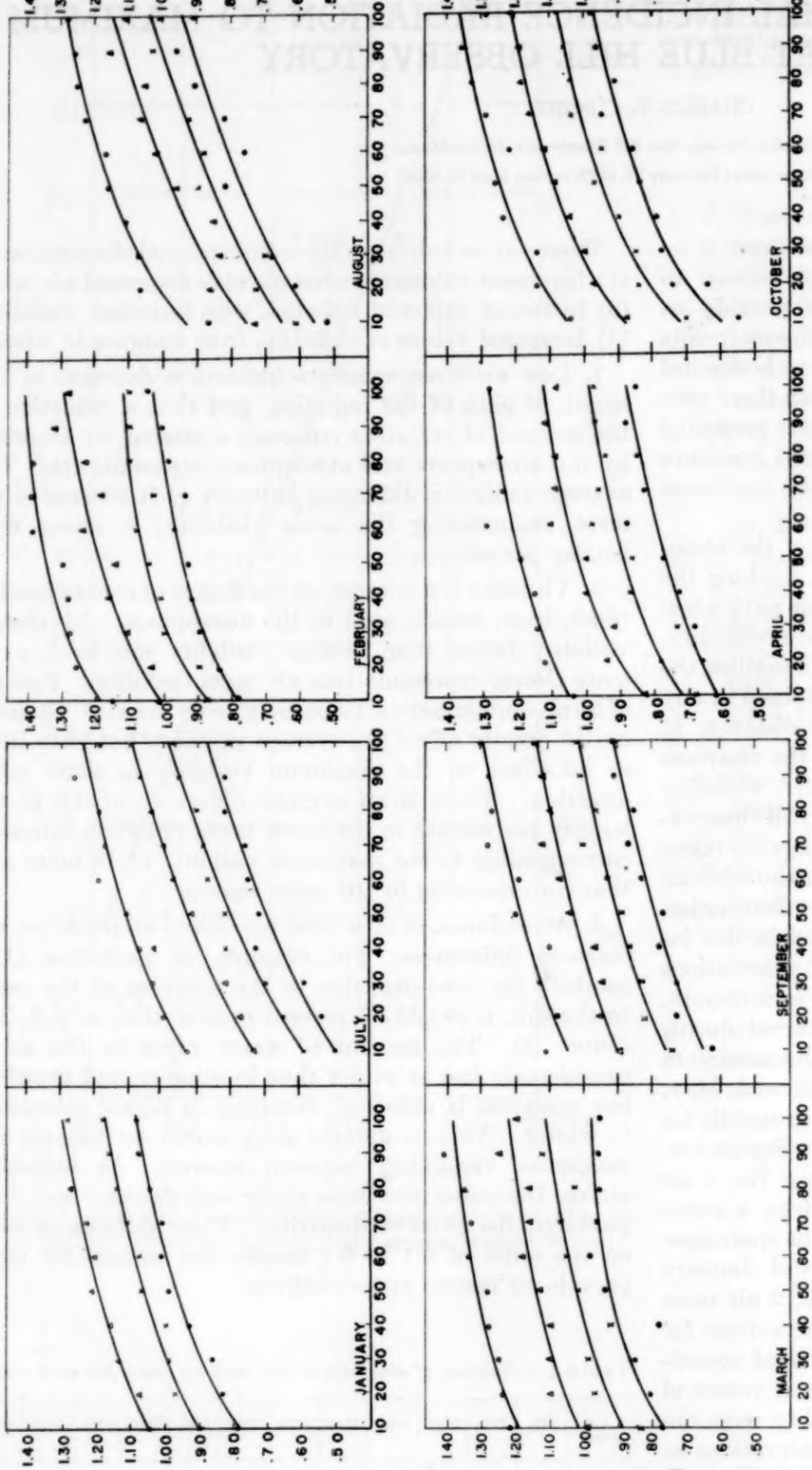

FIGURE 1.—Plots of mean values of solar radiation for each 10-mile multiple of visibility and subdivided according to air mass. Months are paired to show maximum variability between seasons.

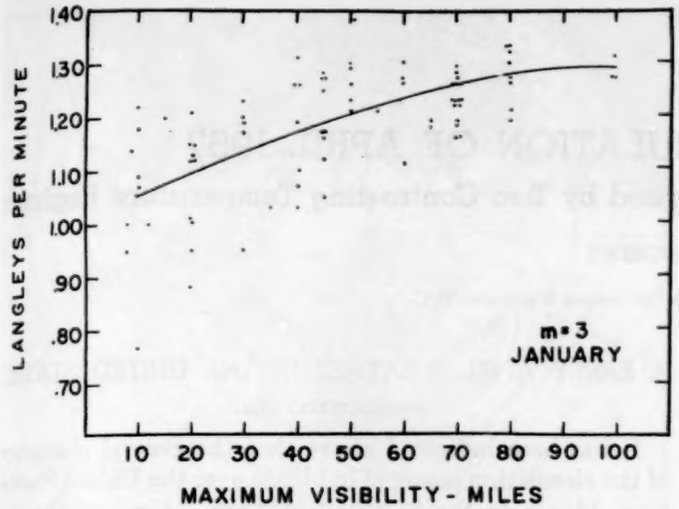

FIGURE 2.—Plot of all observations of normal incidence radiation, January 1949–56, at air mass 3.

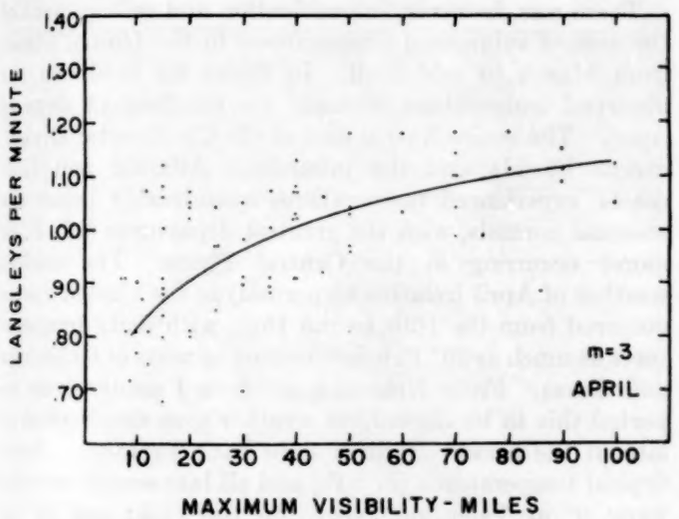

FIGURE 3.—Plot of all observations of normal incidence radiation, April 1949–56, at air mass 3.

Figures 2 to 5 are plots of actual values of all observations for four selected months, with curves fitted by eye to the average values of the plots. These plots show the amount of variability in individual observations to be greater at lower visibilities than at high. This probably means that the observations taken with high visibilities are characterized by a narrower range of water vapor content than those taken with the lower visibilities. That is, when the visibility is very good the air is always dry, but with low visibilities (near 10 miles) the air may be dry or moist. Thus, at high visibilities the seasonal variation due to varying water content is less marked than at low visibilities, for the observations made at high visibilities will have more nearly the same water content that those at low visibilities regardless of season. These plots are a good indication of the amount of variability encountered throughout the entire study.

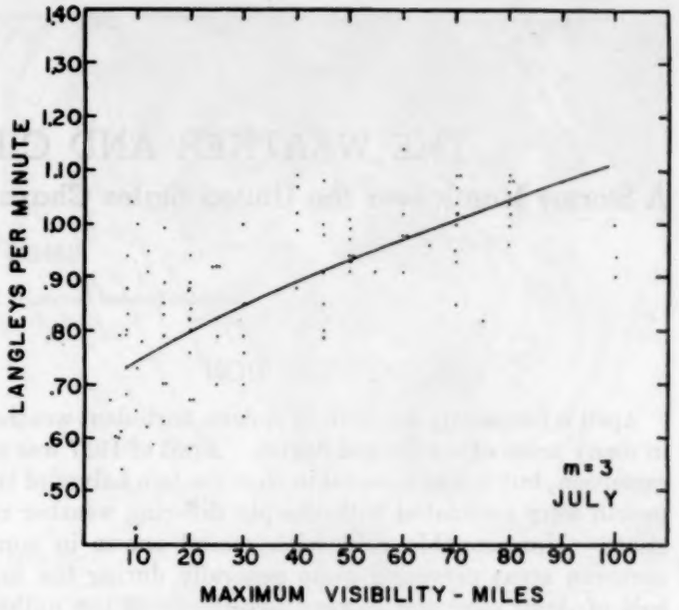

FIGURE 4.—Plot of all observations of normal incidence radiation, July 1949–56, at air mass 3.

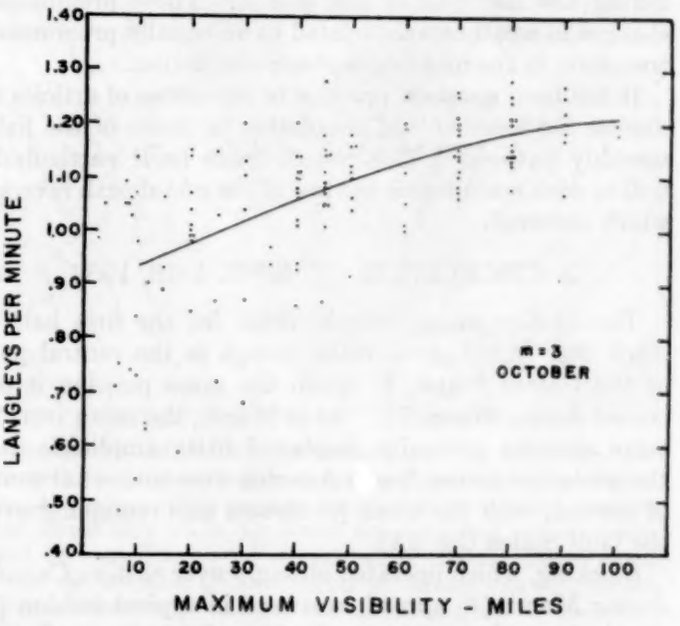

FIGURE 5.—Plot of all observations of normal incidence radiation, October 1949–56, at air mass 3.

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THE WEATHER AND CIRCULATION OF APRIL 1957 [1]

A Stormy Month over the United States Characterized by Two Contrasting Temperature Regimes

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1. INTRODUCTION

April is frequently a month of violent, turbulent weather in many areas of the United States. April of 1957 was no exception, but it was unusual in that the two halves of the month were associated with sharply differing weather regimes. Unseasonable cold with record snows in some northern areas prevailed quite generally during the first half of April over the eastern two-thirds of the nation. Near mid-month this wintry weather was replaced by summerlike conditions with temperatures far above the seasonal normals. In central and eastern Texas excessive rains fell, while very dry weather prevailed in the East during the last half of the month. These pronounced changes in weather were related to an equally pronounced transition in the mid-tropospheric circulation.

It has been common practice in this series of articles to discuss the weather and circulation in terms of the half-monthly patterns. This month lends itself particularly well to such a treatment in view of the mid-month reversal which occurred.

2. CIRCULATION OF APRIL 1–15, 1957

The 15-day mean 700-mb. chart for the first half of April (fig. 1A) shows a mean trough in the central part of the United States, in much the same position it occupied during March [3]. As in March, the mean trough-ridge systems generally displayed little amplitude and the westerlies across North America were somewhat south of normal, with the mean jet stream axis remaining over the Gulf States (fig. 2A).

Blocking, which operated strongly over eastern Canada during March [3], spread westward in typical fashion [7] to Alaska and the eastern Pacific. In early April (fig. 1A) it was represented by the large area of positive 700-mb. height anomaly with centers in eastern Canada (+390 ft.) and the eastern Aleutian Islands (+360 ft.). The westward extension of the Canadian block was associated with a difluent pattern in the eastern Pacific. During this period a new block made its appearance in the North Atlantic. This is shown as a closed anticyclone over Great Britain, along with a height anomaly center of +370 ft.

[1] See Charts I–XVII following p. 140 for analyzed climatological data for the month.

3. EARLY APRIL WEATHER IN THE UNITED STATES

UNSEASONABLE COLD

It has been indicated above that the general character of the circulation changed but little over the United States from March to the first half of April. Similary the related average weather conditions displayed considerable persistence for the two periods.

There was, however, intensification and enlargement of the area of subnormal temperatures in the United States from March to mid-April. In figure 3A is shown the observed temperature anomaly for the first 15 days of April. The entire Nation east of the Continental Divide, except Florida and the immediate Atlantic and Gulf coasts, experienced temperatures considerably below the seasonal normals, with the greatest departures (10° F. or more) occurring in the Central Plains. The coldest weather of April (relative to normal) in the United States occurred from the 10th to the 15th, with daily temperatures as much as 30° F. below normal in parts of Oklahoma and Texas. From Nebraska southward many areas reported this to be the coldest weather ever experienced so late in the season (records date back to 1887). Some typical temperatures (in ° F., and all late-season records) were: 9° at Valentine, Nebr., on the 12th; and 18° at Springfield, Mo., 20° at Oklahoma City, Okla., and 31° at Dallas, Tex., all on the 13th.

This vast area of unseasonable cold can be related to a deeper than normal trough in the United States and to northeasterly anomalous flow that extended from western Canada to the central United States (fig. 1A). Since this anomalous flow was at right angles to the normal thickness isopleths (1000 mb.–700 mb.) [10], it resulted in strong cold advection [8]. The failure of cold polar airmasses which moved into the United States from central Canada to penetrate west of the Divide resulted in temperatures near or slightly above normal in the Far West (figs. 1A and 3A). In the Southeast southwesterly anomalous flow and above normal 700-mb. heights were associated with temperatures near or above seasonal normals

PRECIPITATION AND STORMINESS

The precipitation pattern for the first 15 days of April (fig. 4A) shows that the heaviest amounts fell in the eastern half of the Nation, where totals of 4 inches or

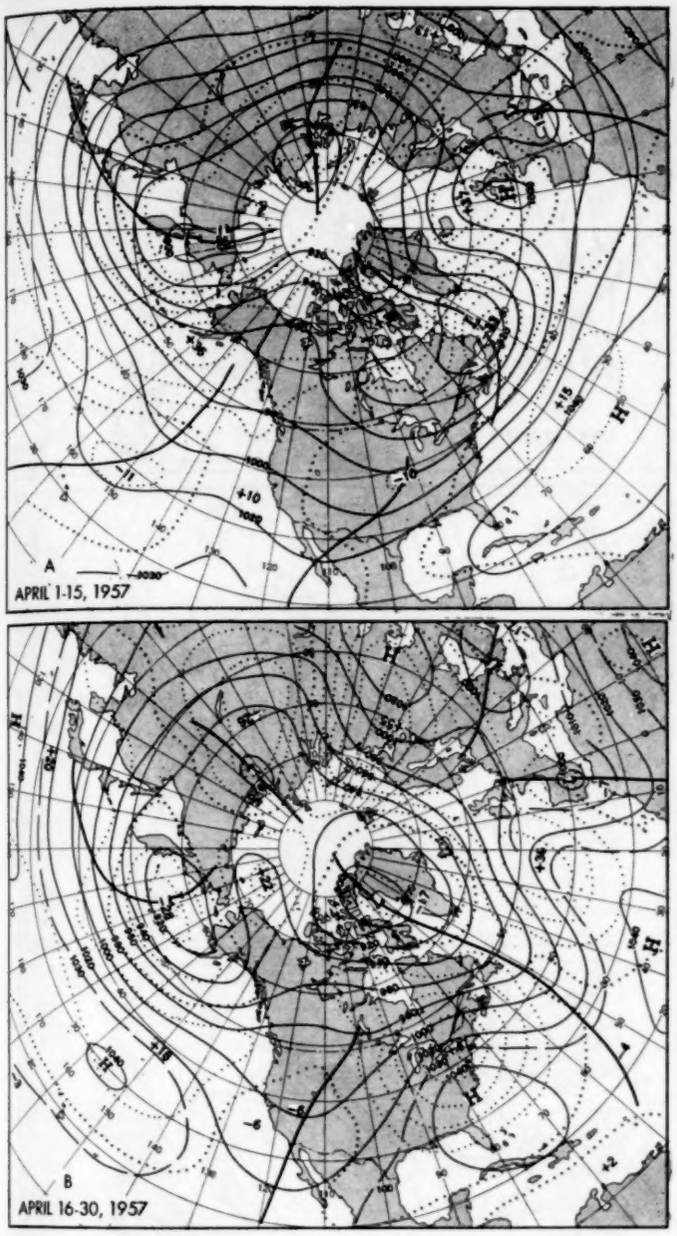

FIGURE 1.—Fifteen-day mean 700-mb. height contours (solid lines) and departures from normal (dotted lines) (both in tens of feet) for (A) April 1–15, 1957, and (B) April 16–30, 1957. Disappearance of the eastern Pacific trough and rapid development of ridge conditions in the eastern United States during second half of month were related to sharp changes in weather regime.

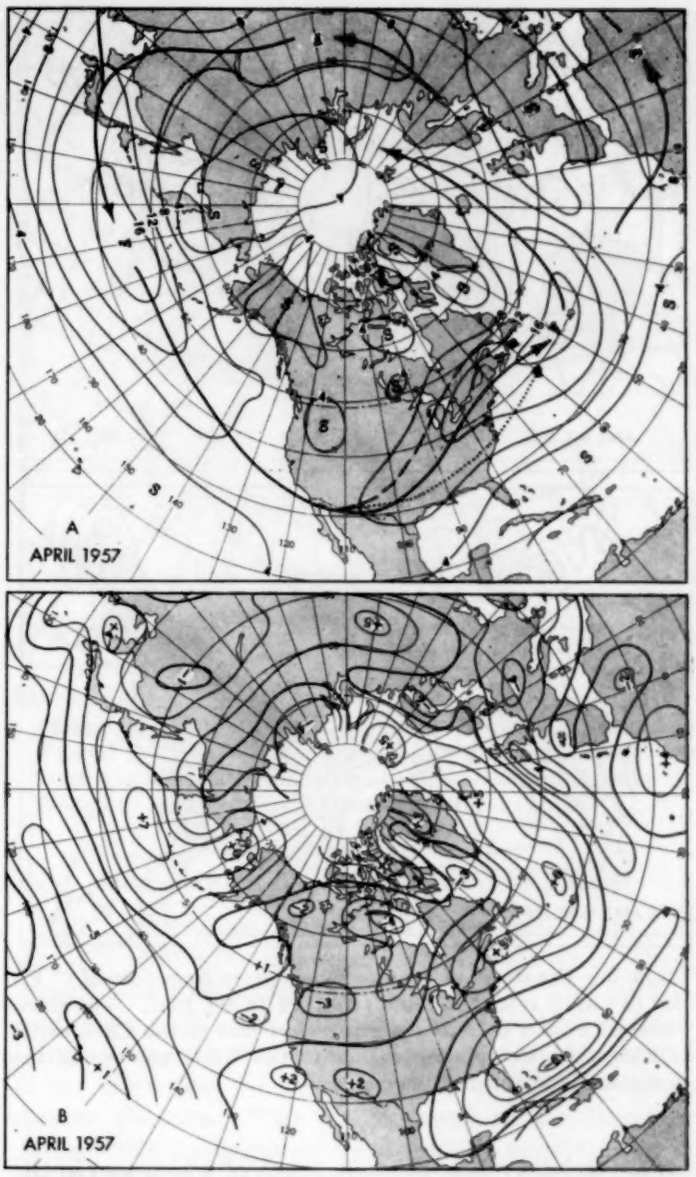

FIGURE 2.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for April 1957. In (A) position of the primary jet axis is given by solid arrow for the month as a whole, by dotted arrow for first half of month, and by dashed arrow for second half of month. Rapid northward displacement of the westerly jet stream axis over eastern United States from the first half to the last half of the month was associated with pronounced surface warming and drying.

more were common from the Ohio Valley to the Gulf of Mexico. As much as 9 inches was observed at Mobile, Ala. Heavy amounts (3 inches or more) also fell along the eastern slopes of the central Rockies and along the north Pacific coast. The Plains States and most of the Southwest received additional precipitation to further alleviate the drought. In the Far Southwest no rainfall was observed during this period.

This nationwide precipitation pattern can be related quite readily to the corresponding half-monthly 700-mb. chart (fig. 1A) in terms of Klein's schematic precipitation model [4]. Heavier amounts in the East and Southeast were associated with confluence and stronger than normal southwesterly flow which advected moisture from the Gulf of Mexico. To the west of the trough, precipitation was mostly light as a result of northwesterly flow which was stronger than normal.

An exception was along the eastern slopes of the Central Rockies, where orographic lifting and overrunning of polar airmasses by tropical airmasses from the Gulf of Mexico

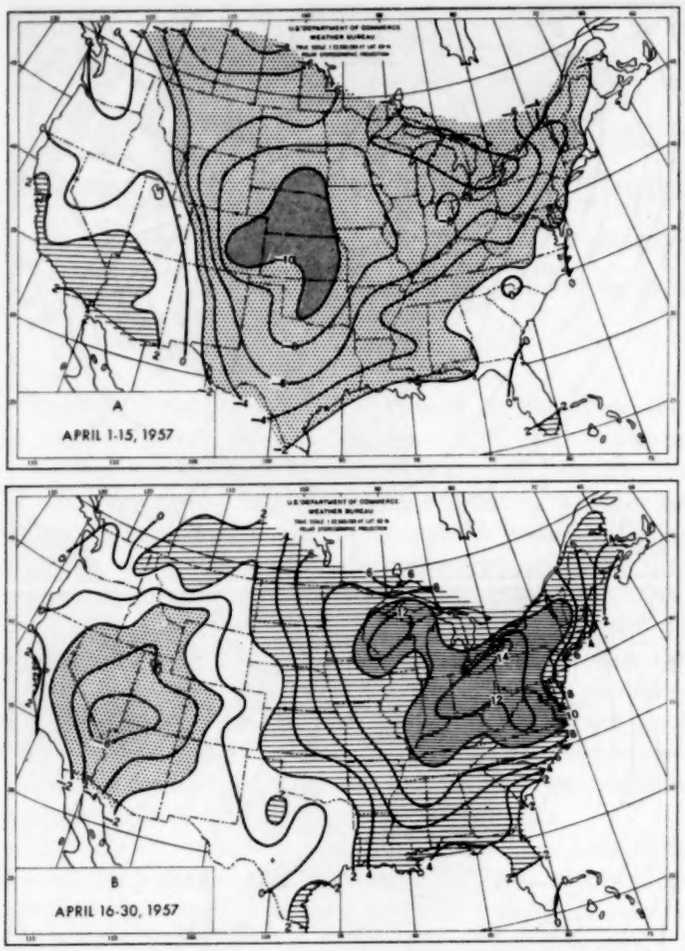

FIGURE 3.—Departure of average temperature from normal (° F.) for (A) April 1–15, 1957, and (B) April 16–30, 1957. The sharp reversal from a cold to a warm regime east of the Continental Divide, with an opposite change in the West, was one of the outstanding features of the month.

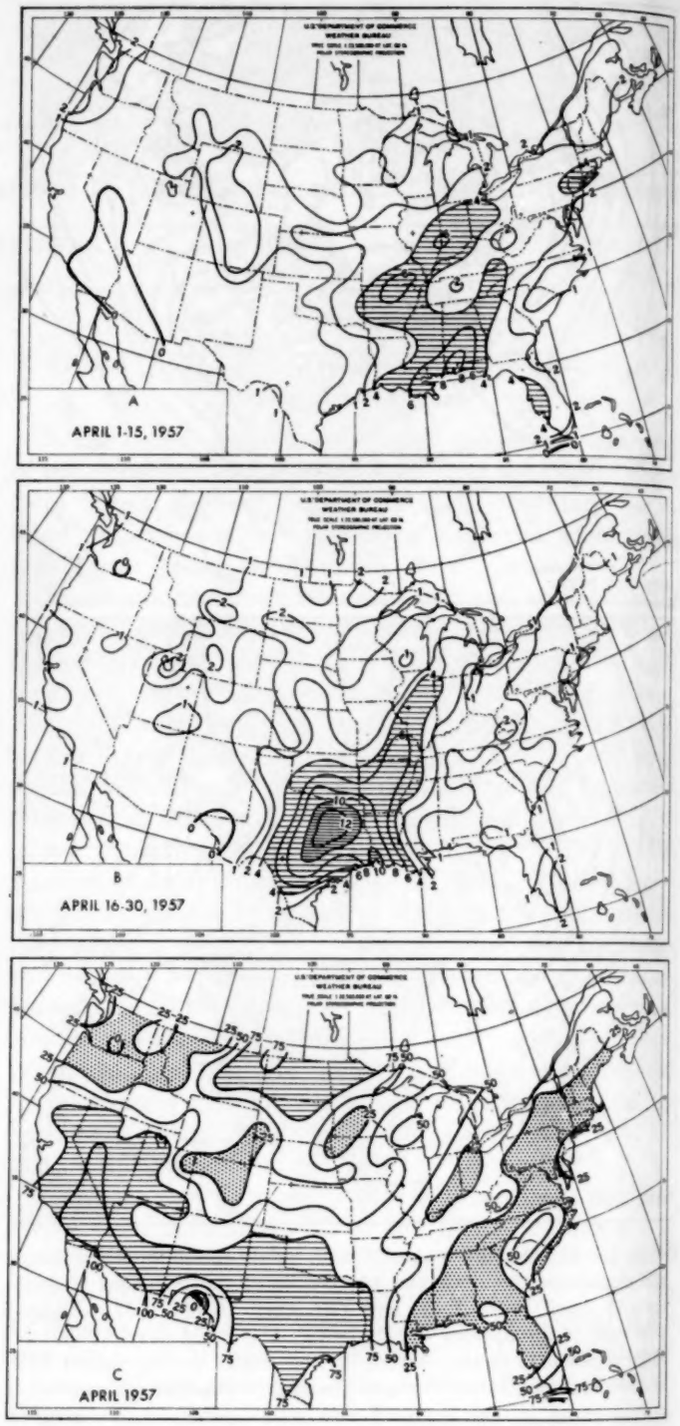

FIGURE 4.—Observed precipitation (approximate) in inches for (A) 1930 EST March 31 to 1930 EST April 15, 1957, and (B) 1930 EST April 15 to 1930 EST April 30, 1957. Areas with amounts greater than 4 inches are hatched. (C) Percentage (approximate) of the total April 1957 precipitation which fell during second half. Stippling indicates under 25 percent; hatching, over 75 percent.

resulted in heavy precipitation, much of which was in the form of snow. Most of this snow fell during two storms, both having their origin in the Southwest about 1 week apart (fig. 5A). Some typical snowfall amounts were: 19 inches (April 1–3) at Lander, Wyo., and 17 inches (April 2) at Denver, Colo. The moderate to heavy snows resulting from these storms extended eastward with several cities, including Sioux Falls, S. Dak (10.7 in.), Fort Wayne, Ind. (10.6 in.), and Toledo, Ohio (12.0 in.), establishing new total snowfall records for April. Unseasonable snow also fell along the east coast when a South Atlantic coastal storm helped establish new late-season snowfall records at Lynchburg, Va. (2.8 in.) and Atlantic City, N. J. (1.0 in.) on the 13th (fig. 5A).

Severe weather activity, in the form of thunderstorms, heavy rain, hail, and strong winds, was frequent during the period April 1–15 from Texas to the Middle Atlantic coast. Much of this storminess was frontal in nature, as suggested by the high frequency of fronts in that area (fig. 6). Tornado activity also occurred as far northeastward as southern Virginia. One of the worst of these storms swept across Dallas, Tex., on the 2d, causing some fatalities and much property damage. In addition, on this date there were 42 tornadoes and funnel clouds

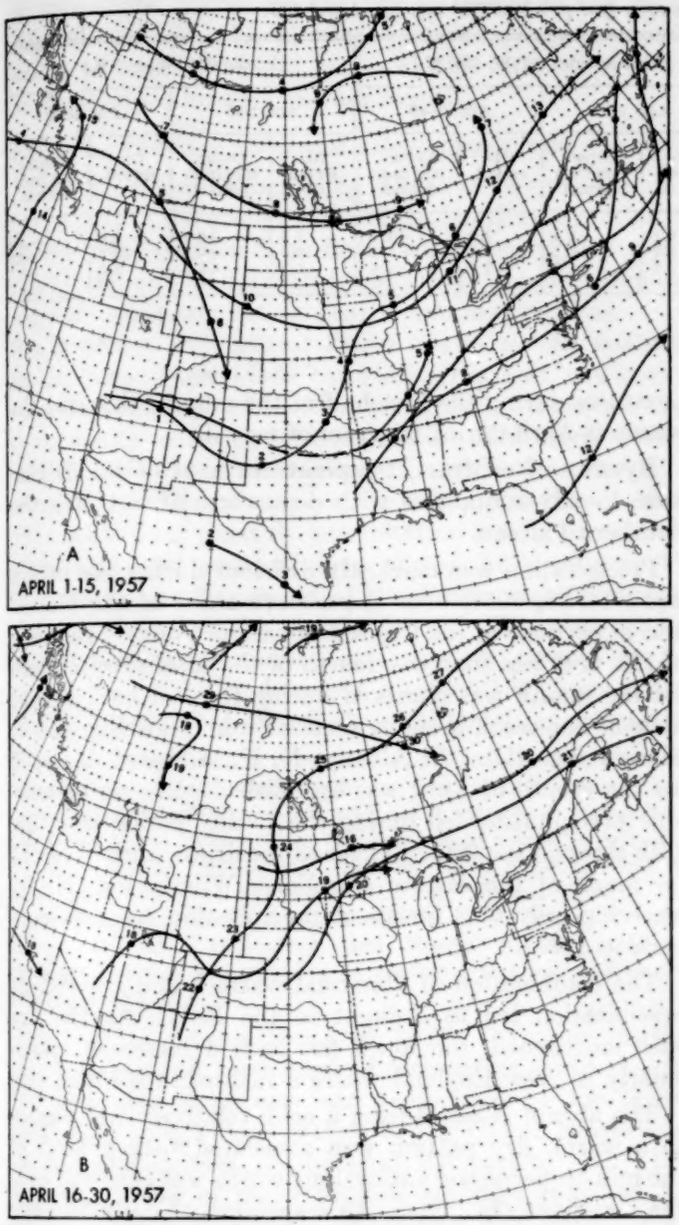

FIGURE 5.—Tracks of centers of cyclones at sea level for (A) Apr 1–15, and (B) April 16–30, 1957. Dots indicate position of center at 0730 EST. Dashed line in track indicates reformation at new position. Northward shift of storm tracks during the last half of the month was related to corresponding displacement of jet stream (fig. 2A) and to pronounced anticyclogenesis in the eastern United States (fig. 1).

reported in the United States, more than on any other day during the first half of the month.

A rather severe north Pacific coastal storm with wind gusts to 70 m. p. h. on the 14th brought heavy rains to that area, although much of the region's precipitation for the period was related to cold fronts associated with storm systems moving through British Columbia (figs. 4A and 5A).

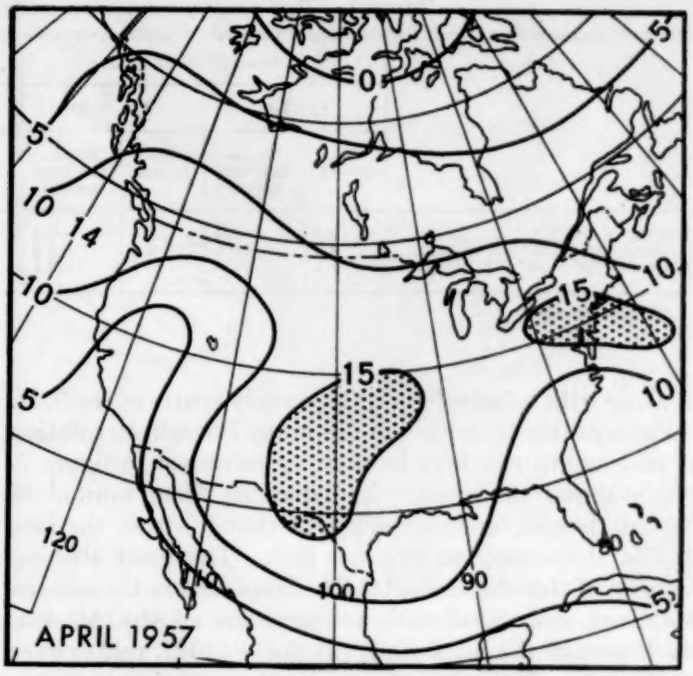

FIGURE 6.—Number of days in April 1957 with fronts of any type (within squares with sides approximately 430 nautical miles). Frontal positions taken from *Daily Weather Map*, 1330 EST. High frequency of fronts in the south-central United States was related to heavy rains and storminess in that area.

4. MID-APRIL CIRCULATION TRANSITION

The 15-day mean 700-mb. chart for April 16–30, 1957 (fig. 1B) shows the disappearance of the eastern Pacific trough that was present earlier in April. The resulting long wavelength was relieved when the United States trough retrograded by some 15° to 20° of longitude, while at the same time the western Pacific trough progressed a similar distance. This readjustment of the long-wave pattern was accompanied by increasing amplitude of the trough-ridge systems over the United States and the Atlantic.

Blocking was also present in varying intensity during the last half of April. The surge over Alaska earlier in the month continued to retrograde and can be identified with the +220-ft. height anomaly center over the Arctic Basin (fig. 1B). Only remnants of the Canadian block remained, identified by positive height anomalies in that area. In this connection it is difficult to ascribe any continuity to the +390-ft. height anomaly center in figure 1A. However, from a study of 5-day mean 700-mb. height anomaly charts, this center appears to have contributed very little to the +470-ft. center over the northeastern United States in figure 1B. This latter center, and its associated closed upper-level High, was largely the result of rapid dynamic anticyclogenesis. The early April block in the Atlantic was now farther south and amalgamated with the low-latitude ridge, while a new and intense block appeared over western Russia (fig. 1B). The latter block had an extensive upper-level anticyclone associated with

TABLE 1.—*Half-monthly mean zonal westerly values (m. p. s.) at 700 mb. for April 1957*

Index	Atlantic (5° W.–65° W.)				North America (65° W.–135° W.)				Pacific (135° W.–145° E.)			
	Apr. 1–15		Apr. 16–30		Apr. 1–15		Apr. 16–30		Apr. 1–15		Apr. 16–30	
	Observed	Departure from normal	Observed	Departure from normal	Observed	Departure from normal	Observed	Departure from normal	Observed	Departure from normal	Observed	Departure from normal
Polar (55° N.–70° N.)	0.8	−3.4	7.6	+3.4	0.6	−4.4	6.9	+1.9	1.8	+0.7	*−2.3	−3.4
Temperate (35° N.–55° N.)	8.7	+0.5	6.9	−1.3	7.7	+0.1	7.4	−0.2	10.0	+0.6	12.8	+3.4
Subtropical (20° N.–35° N.)	7.1	+0.8	4.2	−2.1	7.6	+1.3	2.7	−3.6	4.7	−1.5	2.5	−3.7

*Represents easterly flow.

it, along with a 700-mb. height anomaly center of +550 ft.

Perhaps this transition in the mean 700-mb. circulation at mid-month can best be seen by reference to figure 7, which shows the change in departure from normal of 700-mb. height (anomalous height change) from the first half of the month to the last half. The most striking features of this chart are: (1) The large falls in the eastern Aleutians, associated with retrogression of the Alaskan block toward the northwest; (2) the +520-ft. center over northeastern United States, related to anticyclogenesis in the east; and (3) the +700-ft. center over northwestern Russia, associated with the new block.

These changes in general circulation can also be related to regional changes in zonal index. In table 1 is given a list of the various indices at 700 mb. for each half of the month along with their departures from normal. Relaxation of blocking over Canada and the North Atlantic was accompanied by a sharp rise in the polar westerlies, a slight diminution in the zonal westerlies, and a considerable decrease in the strength of the subtropical westerlies. Amplification of the early April planetary waves over the United States and western Atlantic (fig. 1) was associated with a marked northward displacement of the mean jet stream axis (fig. 2A). Over the United States this transition from a zonal-type flow pattern to a more meridional type was accompanied by a pronounced change in weather regime.

5. LATE APRIL WEATHER IN THE UNITED STATES

THE "HEAT WAVE" AND INCREASING DROUGHT IN THE EAST

The unseasonable cold in the eastern two-thirds of the Nation early in April was replaced by unseasonable warmth over a vast area during the latter half of the month (fig. 3). From the Great Plains to the Middle Atlantic States the anomalous temperature change between the two halves of April was as much as +15° to +20° F.

A wide area from Minnesota to Virginia experienced average temperatures of 10° F. or more above normal, with Buffalo, N. Y., reporting a departure of +14° F. and an all-time record maximum temperature for April of 87° F. on the 24th. A similar record was established at Escanaba, Mich., with 82° F. on the 29th. In much of the area from the Lower Ohio Valley to Virginia the period April 20–28 [6] was the longest April "heat wave" ever recorded. At Richmond, Va., in spite of subnormal temperatures during the first half of the month, this was the warmest April during 60 years of record.

By way of contrast, temperatures west of the Divide were mostly subnormal with departures of −6° F. in the Southern Plateau.

Precipitation was markedly deficient during the period April 16–30, 1957, over the eastern third of the Nation and in portions of the Upper Mississippi Valley. In much of this area less than one-fourth of the total precipitation for the month was observed during the last half, and as little as one-tenth in many sections from New England to Florida (fig. 4C). At Albany, N. Y., a record dry spell for the month of April was established when no measurable precipitation fell during the 17-day period from the 13th through the 29th. This was the driest April of record for much of the eastern Carolinas, Wilmington, N. C., receiving only 0.33 inches of precipitation (records date back to 1871).

The combination of abnormal warmth and insufficient precipitation led to drought in the East. As the dry spell lengthened, the forest fire hazard increased, particularly in New England where a rash of fires broke out.

The abrupt reversal from a cold, relatively wet regime to a warm, dry pattern was associated with growth of the mid-tropospheric anticyclone which was centered over the Carolinas (fig. 1B). An inspection of daily 700-mb. charts reveals that this warm cell became firmly established over the Carolinas shortly after mid-month. The circulation around this High affected the weather pattern from the Divide to the Atlantic Coast. Note how well the temperature anomaly pattern corresponds to the 700-mb. height departure from normal field (figs. 3B and 1B) in the usual relationship [5]. Anticyclonic curvature and wind shear, associated with large-scale subsidence, can be related to the dry regime in the East. In addition the mean westerly jet axis and associated storm tracks shifted far northward, leaving the East completely free of any migratory cyclonic activity (figs. 2A and 5).

Over the Northern Plains, California, and the central and southern Plateau States most of April's precipitation fell during the latter half of the month (fig. 4C). Much of this was related to two short-wave troughs moving through the mean ridge off the Pacific Coast, and to subsequent marked surface development occurring as

these troughs moved into the mean trough in the West (figs. 5B and 1B). Locally heavy amounts were observed, and a 24-hour fall of 2.41 inches at Salt Lake City, Utah on April 22–23 broke a 28-year record.

THE TEXAS FLOODS AND SUBSTANTIAL DROUGHT RELIEF IN THE SOUTHWEST

The trend toward increasing rainfall since the beginning of the year in the drought area of the Southwest continued during the latter half of April, when record and near-record amounts of rain fell from central Texas to Illinois, with excessive amounts in central and eastern Texas. In the southern and central Plains States severe weather, in the form of tornadoes, thunderstorms, hail, and heavy rain showers, was a frequent occurrence. This activity occasionally extended into the middle Mississippi Valley and the Great Lakes region. In table 2 is shown a representative list of cities in the heavy rain belt of April 1957 with their monthly precipitation totals, percentage of normal, and appropriate remarks. It is noteworthy that more than 90 percent of the Texas rains fell during the second half of the month (fig. 4). These seemingly incessant rains culminated in extensive flooding late in the month. Quoting from the April 29, 1957 issue of the *Weekly Weather and Crop Bulletin, National Summary* [11],

> Following a long period of drought, east and central Texas received excessive amounts of rainfall, filling reservoirs and causing widespread flooding. Beginning April 18, heavy rains have been a daily occurrence in the area. Waco, Texas reported a total in excess of 13 inches during the period. However, some areas received as much as 7 inches in less than 24 hours. Serious flooding has developed in such major streams in Texas as the Sabine, Trinity, Brazos, Colorado, Guadalupe, and Nueces Rivers. Light to moderate flooding was reported in eastern Oklahoma and southwestern Arkansas.

Synoptically, conditions were highly favorable for the development and persistence of such severe weather. At 700 mb. this storminess can be related to the large-amplitude trough-ridge system in the United States and to the concomitant height anomaly pattern (fig. 1B). Vast quantities of moist tropical air were advected by strong south-southeasterly anomalous flow components at 700 mb. from the Gulf of Mexico into the Southern Plains. Here this moisture was released as a result of rising motion in a quasi-stationary frontal zone (fig. 6) between cold Pacific air to the west and warm tropical air to the east (fig. 3B). It is noteworthy that the heaviest rains fell under cyclonic southwesterly flow at 700 mb. about halfway between trough and ridge, the optimum place for heavy precipitation and upward vertical motion according to Klein [4]. The 700-mb. departure from normal height pattern (fig. 1B) associated with these rains is also quite similar to the results of Martin and Hawkins [5] and Stidd [9] in later precipitation studies. Stidd, by use of correlation fields relating mean monthly 700-mb. height and monthly precipitation averaged over a given State, found that for Texas (and Arkansas) the heaviest rains occurred when pressures were above normal in the East and below normal in the Southwest. Martin and Hawkins obtained similar results by relating the 10 wettest 5-day mean periods at Fort Worth, Tex. to their corresponding 700-mb. height and height anomaly fields. It must be noted, however, that all these studies related to winter cases, so that their applicability to spring may be questioned.

The meridional circulation pattern in the United States (fig. 1B) resulted in a strong surface thermal gradient from Texas to the northern Rockies (fig. 3B), with a resultant high frequency of surface fronts in the central and southern Plains States (fig. 6). Advection of cold maritime Pacific airmasses into and through the mean trough, replacing and lifting warm tropical airmasses, triggered much of the violent weather. Many of the tornadoes in the Plains States were of the "cyclonic type" and were associated with cold fronts and squall lines southeast of the migratory cyclonic centers (fig. 5B). More tornadoes

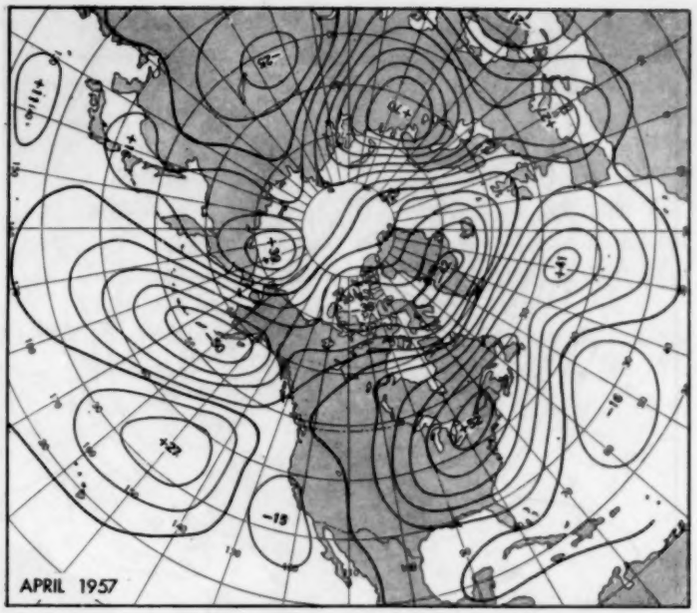

FIGURE 7.—Mean 700-mb. anomalous height change (in tens of feet) from April 1–15 to April 16–30, 1957. Areas of large change were associated with marked reversal of the planetary circulation.

TABLE 2.—*Selected precipitation records established during April 1957*

Station	Precipitation (inches)	Percent of normal	Remarks
Del Rio, Tex.	6.49	447	April record.
Dallas, Tex.	13.85	358	Do.
Fort Smith, Ark.	10.32	230	Do.
Wichita Falls, Tex.	8.50	361	Do.
Shreveport, La.	11.19	244	Do.
San Antonio, Tex.	9.32	308	2d wettest April.
Fort Wayne, Ind.	7.11	219	Do.
Springfield, Ill.	8.86	259	Greatest since 1893.
Little Rock, Ark.	11.34	220	Greatest since 1927.
Lake Charles, La.	13.71	321	Greatest since 1940.
Waco, Tex.	13.37	337	

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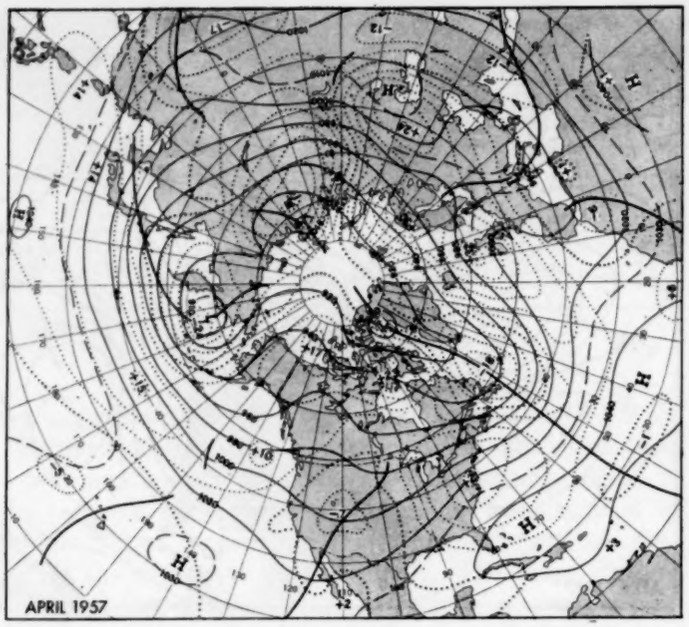

FIGURE 8.—Mean 700-mb. height contours (solid lines) and departures from normal (dashed lines) (both in tens of feet) for April 1–30, 1957. Major circulation features over North America were the trough-ridge system in the United States and blocking across Canada.

and funnel clouds (53) were observed on the 22d than on any other day of April. Late in the month, when high pressure covered most of the United States and cyclonic activity was at a minimum (fig. 5B), the tornadoes in the Southern Plains were of the "convective type" and were associated mainly with weak surface pressure troughs.

While heavy rains and floods occurred in central and eastern Texas, little if any precipitation fell in the southwestern portion of that State (fig. 4), and the drought there continued. This deficiency of precipitation can probably be related to downslope motion in greater than normal southwesterly flow aloft (fig. 1B).

6. MONTHLY SUMMARY

As might be expected, the mean monthly 700-mb. chart for April (fig. 8) displays many of the features present on the half-monthly mean charts (fig. 1). However, the disappearance of the full-latitude eastern Pacific trough from the first half to the last half of April is reflected on the monthly chart as only a minor mid-latitude trough. The result is a rather long wave spacing between the Asiatic coastal trough and the United States trough. In view of the transition in circulation that occurred near mid-month, such a long wavelength is quite reasonable.

Monthly mean wind speeds at 700 mb. were strongest across the Atlantic and over the western Pacific, where speeds were 7 m. p. s. above normal (fig. 2B). At sea level this strong westerly flow was associated with deeper than normal Aleutian and Icelandic centers of action, the former being 11 mb. below normal while the latter averaged 9 mb. below the April normal (Chart XI).

TABLE 3.—*Tornadoes and funnel clouds observed in the United States during April 1957 (preliminary figures)*

Period	Tornadoes	Funnel clouds (not reaching the ground)	Total
Apr. 1–15	102	26	128
Apr. 16–30	135	133	268
April 1957	237	159	396

The monthly temperature and precipitation patterns (Charts I–B, II, and III) bear a normal relationship to the monthly 700-mb. height pattern and anomaly field (fig. 8) in a manner discussed previously for the half-monthly patterns. Especially important was the prevalence of southeasterly anomalous flow at sea level (Chart XI, inset) in the eastern half of the United States. This flow imported large quantities of Gulf moisture northward, where it later was released in varying amounts of precipitation from the Divide to the Atlantic Coast.

Both the monthly mean 700-mb. and sea level charts (fig. 8 and Chart XI) are strikingly similar to Beebe's composite charts for tornado occurrence for the central and southern Plains States [1], the area of most severe storminess during April 1957. In table 3 is given a summary of the number of tornadoes and funnel clouds which were observed in the United States during the month. Exclusive of the latter, the total of 237 tornadoes reported is an all-time April record, and more than double the previous record of 114 in April 1956 [2]. Much of this pronounced increase can be attributed to marked differences in the general circulation between the two Aprils. Similarly, the sharp increase in tornadic activity from the first half to the last half of this April was related to the transition in circulation which occurred at mid-month, as discussed in section 4.

Soil moisture in the Southwest now extends deeper than it has for five years, but it will take considerable time to rebuild the underground water storage. Although it is not possible to predict with complete confidence the break of the long-period drought, the trend established by the large-scale general circulation patterns this year offers hope that it is over. And although there was much damage from floods and violent weather, the benefits to agriculture can hardly be overestimated.

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THE EASTERN STATES HEAT WAVE OF APRIL 20–28, 1957

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1. INTRODUCTION

Temperatures during the month of April averaged above normal over practically all of the eastern half of the United States. Most States within the area east of the Mississippi River were either entirely or partially contained within the +2° C. anomaly isopleth. Most of the area of North Carolina, Virginia, Maryland, Delaware, and West Virginia was enclosed by the +4° F. anomaly, and a small portion of Virginia and Maryland was encircled by the +6° F. anomaly isopleth [1]. These limited values do not in themselves confirm a pronounced and prolonged heat wave during this month. However, an examination of weekly anomalies in the *Weekly Weather and Crop Bulletin* [2] or in figure 3A in the article by Andrews [3] indicates that the monthly anomalies were definitely weakened by the subnormal temperatures present over the East during the first half of the month.

The transitional period from below normal to above normal temperatures was of ephemeral duration. This was manifest by comments entered on the April Local Climatological Data forms and as specifically expressed by the Green Bay, Wis., Meteorologist in Charge: "Overnight in the middle of the month weather turned from March type to late May type." Much of the East was under the influence of this heat wave throughout the latter half of the month and thus the semimonthly temperature chart as presented by Andrews [3], figure 4B, depicts a large +10° F. anomaly area.

The higher temperatures occurred, for the most part, during the period of April 21–28. Generally, it was within this interval that many stations recorded readings that equaled or exceeded records previously established for these dates. However, the occurrence of new maximum temperatures for the month of April was reported by only a few first order stations.

2. ANTECEDENT CONDITIONS

Two distinct weather patterns existed over the United States during the month of April with the initial regime being nearly a complete reversal of the second. Chronologically this reversal of pattern occured almost precisely at the mid-point of the month. (See fig. 1 of Andrews [3].) Generally the upper-air picture during the first two weeks of April 1957 was characterized by trough-ridge systems of small amplitude over the United States.

A slow eastward progression of the long-wave trough-ridge positions prevailed over the North Atlantic in this initial 2-week period with the trough line in evidence along the east coast by the end of the fortnight. Simultaneously with the eastward drift of the planetary patterns were the more frequent and faster-traveling short-wave troughs and ridges which traversed these long-wave patterns.

Moderately strong zonal flow at 500 mb. was prevalent over the eastern United States during the first half of the month and it extended westward to the Pacific during the last 10 days of this period. This upper flow resulted in a dynamic succession of pressure systems on the surface chart in association with the previously mentioned short-wave troughs and ridges plus a resultant rapid interchange of airmasses. The jet stream was located close to the normal April position west of the Continental Divide but east of that area it was displaced approximately 5° southward. In this anomalous position it was associated with a similar southward displacement of the polar front and related storm tracks. The result of these factors was illustrated by the occurrence of below normal temperatures and above average precipitation over the eastern States during the first 15 days of April.

Between the 13th and the 18th of the month a significant change occurred in the pressure patterns of the troposphere. In part, this rapid and pronounced transition was occasioned by a readjustment in the long-wave trough pattern over the Northern Hemisphere. Related to the adjustment of westerly wavelengths was the placement of a low-latitude long-wave trough over the west coastal area of the United States, as well as the rapid progression of the long-wave ridge into the eastern half of the country. In the western Atlantic region the long-wave trough advanced to near 45° W., where initially it weakened. Upon attaining these positions the eastward progression of the long-wave features decelerated and became practically stationary. However, shortly after the 18th of the month the amplitude of major surface and upper-air troughs and ridges increased and strong meridional flow developed. Concomitantly the jet stream recurved northward over eastern United States. Cyclonic and frontal activity was restricted to the western portion of the country. Thus, pressure patterns had become favorable for an early spring heat wave and a period of light rainfall over the eastern United States.

3. SYNOPTIC CONDITIONS

High pressure blanketed the eastern half of the United States on April 18, 1957, as it had for the previous 2 days. It was associated with a large polar High that had moved southeastward from Canada passing across the Great Lakes and the Middle Atlantic States. From the center of this old Canadian High, now 1033 mb. and located near 37° N., 47° W., extended two elongated ridges, one stretching inland over North Carolina to eastern Arkansas and the other reaching northwestward over Massachusetts into Northern Ontario. High centers in this latter ridge were weak as may be observed on the 1830 GMT chart (fig. 1A). The returning flow from this large but modified polar airmass was now spreading westward and northward over the eastern and east-central States. A weak warm front associated with this southerly or southeasterly flow of transitional polar air lay across the northern and north-central tier of States. It stretched from Maryland to northern Illinois and thence into a Low centered over southwestern Wyoming. In the Gulf States the airmass was acquiring tropical maritime characteristics.

In the ensuing hours ending 1830 GMT April 20, the Wyoming cyclone progressed into North Dakota where it weakened as cyclogenesis occurred along the trailing stationary front over western Kansas. These two areas of low pressure continued to advance northeastward and eastward about the periphery of the anticyclone over the eastern United States. The Kansas Low intensified as it reached the northern shore of Lake Superior at the end of the 48-hour period. However, the first Low had continued to dissipate within an area of pronounced troughing in advance of the developing center.

Concomitant with the movement of the Lows was the southeastward and eastward motion of the two highs that had been located in the ridge that extended northwestward from the Atlantic anticyclone center. The northernmost High came to rest off the coast of the Carolinas while the other progressed to a position some 350 miles southeast of Newfoundland. A ridge extending from the polar region southward to Oklahoma, then breaking sharply to the east, interconnected the two Highs with a new anticyclone that was located 100 miles north of Fort Smith, District of Mackenzie.

East of this new Canadian High was an intensifying cyclone near Frobisher, Baffin Island, which in conjunction with the building anticyclone had advected cold air southward, and in so doing had produced a suitable thermal field for the generation of a cold front along the 55th parallel. At the same time the warm front over the eastern and central States had been carried northward into Canada by the moderate southerly flow of warm air south of the front. However, over the New England States this southerly advection had been delayed by the southeastward push of the high cell toward the Carolinas. This resulted in a sharp southward bend on the warm front over Vermont from whence it stretched into eastern Maryland. More precise movements of pressure centers during the period of this study may be examined in Charts IX and X.

Movements of High and Low centers and associated warm and cold fronts were quite pronounced during the next 24 to 48 hours, but most of the pressure field progression occurred over Canada or the New England States. By the end of 24 hours, or 1830 GMT April 21, the Low previously near Lake Superior was approaching Newfoundland, while the Fort Smith High dropped rapidly southeastward to near Moosonee, Ont. Briefly, within this period, New England was located in the warm sector, long enough to establish a few temperature records on this Easter Sunday. Similar maximum temperatures occurred on this day to the south of that region. By evening (GMT) the trailing cold front from the Newfoundland Low was crossing New England, southwestern Pennsylvania, and the southern portions of Ohio, Indiana, and Illinois. Furthermore, the cold front previously along the 55th parallel was in close pursuit of the initial front in the New York and New England sector. High pressure continued off the Carolinas while the surface ridge remained along and just east of the Mississippi River.

In the ensuing hours ending at 1830 GMT April 22, high pressure again enveloped the eastern half of the nation and most of eastern Canada as the Moosonee High progressed southeastward to near Boston, Mass. This anticyclone continued to be interconnected by ridging with other High centers, the nearer two being located over Hudson Bay and 300 miles east of the Georgia coast. By now the cold front had been displaced southward along the east coast to near Cape Hatteras, and in many respects acted similarly to a "back-door" cold front with cooling effects being felt principally east of the Appalachians. Strong southerly flow persisted over the Plains as a new Low formed over western Colorado to aid in the northward transport of warm air.

In the upper-air circulation during this 5-day period the rather broad long-wave ridge which was present on the 1500 GMT chart of April 18 (fig. 1B) increased in amplitude over the East as the adjacent long-wave troughs deepened. Several weak short-wave troughs, in association with the surface Lows, traversed this long-wave ridge across southern Canada. The 700-mb. and the 500-mb. height anomalies were considerably above normal during these five days. From April 19 to 22, at 500 mb. the height departure over the eastern Great Lakes and portions of New York and Pennsylvania exceeded +800 ft. The 1000–500-mb. thickness anomalies indicated on figure 1A, continued to increase during this same period and at times ranged from 600 to 800 ft. above the April normal. Further amplification of the long wave trough-ridge system occurred as indicated by the 5-day 500-mb. and 1000–500-mb. change chart (fig. 2C). On this chart it should be noted that retrogression of the ridge occurred toward the Lake Winnipeg area and that heights increased 200 ft. or more over the northeastern States and south-central Canada. Troughing along the Continental Divide

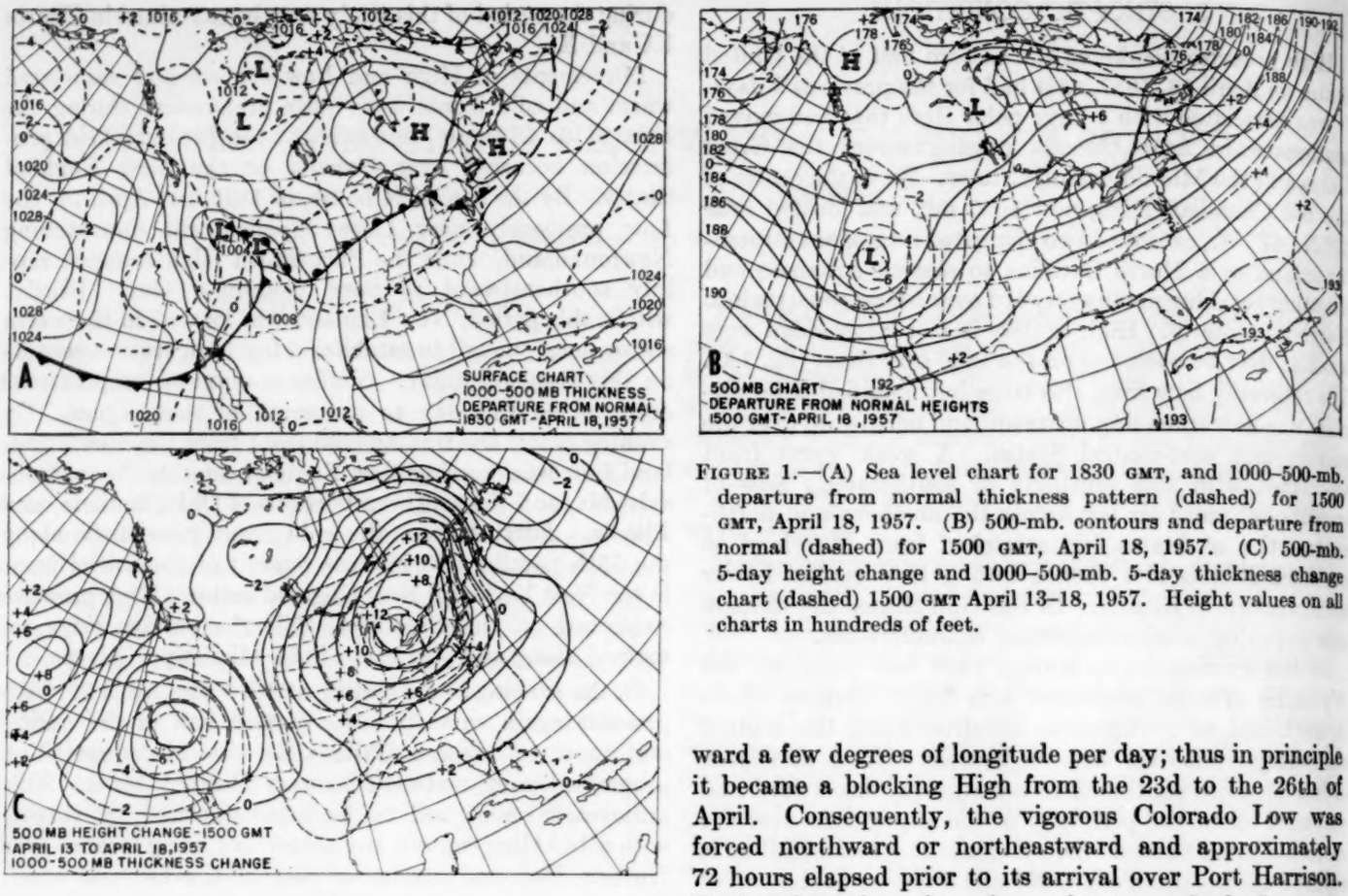


FIGURE 1.—(A) Sea level chart for 1830 GMT, and 1000–500-mb. departure from normal thickness pattern (dashed) for 1500 GMT, April 18, 1957. (B) 500-mb. contours and departure from normal (dashed) for 1500 GMT, April 18, 1957. (C) 500-mb. 5-day height change and 1000–500-mb. 5-day thickness change chart (dashed) 1500 GMT April 13–18, 1957. Height values on all charts in hundreds of feet.

was well defined with falls of as much as 600 ft. Possible ridging was indicated over the West Coast States by the 400-ft. rise over central California. Similar changes may be observed at the 1000-mb. level by graphical subtraction of the two charts represented on figure 2C.

Over eastern North America, by this time, the 700-mb. jet stream was approximately 5° north of its usual April position in the vicinity of Chicago, Ill., and reached a maximum deflection of 10° north of the mean near Caribou, Maine. Thus, with a jet in this position and pronounced blocking directly east of the jet, continuation of mostly fair weather and high temperatures was assured for the area east of the Mississippi River.

Synoptic conditions at 1830 GMT April 23 are shown in figure 2A–B and they present a somewhat repetitious picture of the preceding as well as the ensuing synoptic conditions that prevailed during the heat wave. Illustrated are the persistent High off the Atlantic Coast, the anticyclone over the Hudson Bay region, and the recurrent Low over the western or west-central States. Frontal conditions were similar over the northern portion of eastern United States, southern Canada, and the Central States.

However, during the greater portion of this next 5-day period the movement of pressure centers and fronts proceeded at a much slower pace. The surface High in the vicinity of Port Harrison was retarded, progressing eastward a few degrees of longitude per day; thus in principle it became a blocking High from the 23d to the 26th of April. Consequently, the vigorous Colorado Low was forced northward or northeastward and approximately 72 hours elapsed prior to its arrival over Port Harrison. During these three days the moderate southerly flow over the eastern half of North America was maintained or even intensified as the Low moved into Canada. The trailing cold front over the central States dissipated leaving a cold trough in its stead. But modified tropical air continued to flow northward reaching into portions of southern Canada.

A slight respite from the prolonged heat wave did occur during the early stages of this latter 5-day period, and was occasioned by another "back-door" cold front. The area affected was again the New England States, eastern New York, and the region southward into Maryland. From the 24th through the 26th of April this front remained approximately stationary extending northward from the vicinity of Washington, D. C., to the proximity of, but slightly east of, Buffalo, N. Y. East of the front temperatures were near normal while above normal readings continued in other eastern States.

However, during this period of milder weather a gradual transition occurred in the pressure patterns over the Far West. The eastern portion of the Pacific High progressed onshore as the Colorado Low moved northward into Canada. This eastward push of Pacific maritime air in contrast to the tropical maritime air over the central and eastern portions of the United States developed a sufficient thermal field to produce cold frontogenesis. On the 1830 GMT chart of the 26th this cold front extended from Duluth, Minn., southward to Oklahoma City, Okla., and then curved sharply southwestward.

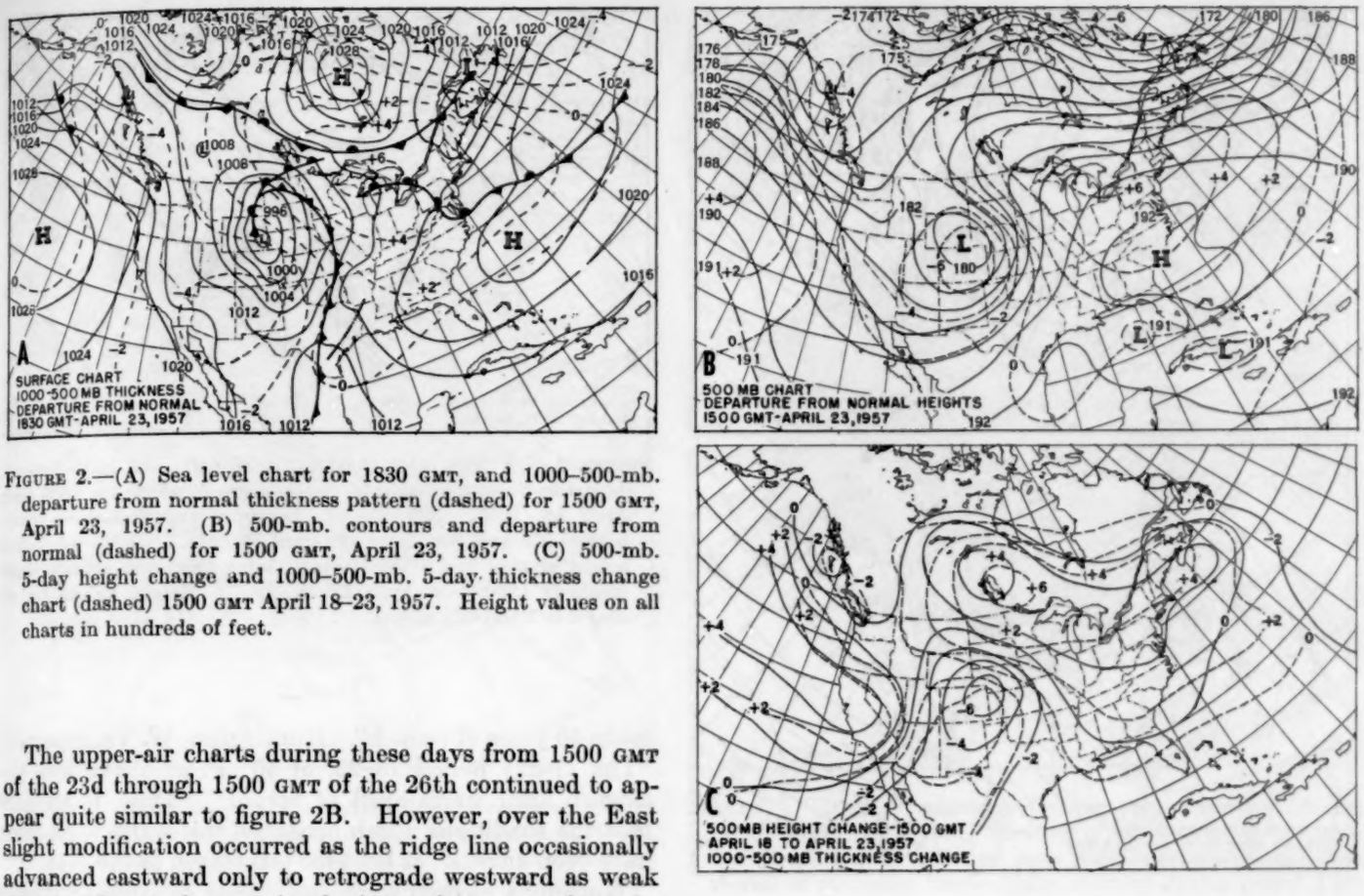


FIGURE 2.—(A) Sea level chart for 1830 GMT, and 1000–500-mb. departure from normal thickness pattern (dashed) for 1500 GMT, April 23, 1957. (B) 500-mb. contours and departure from normal (dashed) for 1500 GMT, April 23, 1957. (C) 500-mb. 5-day height change and 1000–500-mb. 5-day thickness change chart (dashed) 1500 GMT April 18–23, 1957. Height values on all charts in hundreds of feet.

The upper-air charts during these days from 1500 GMT of the 23d through 1500 GMT of the 26th continued to appear quite similar to figure 2B. However, over the East slight modification occurred as the ridge line occasionally advanced eastward only to retrograde westward as weak ridges and attendant anticyclonic vorticity moved northward about the western periphery of the long-wave ridge to reintensify the ridge in its old position.

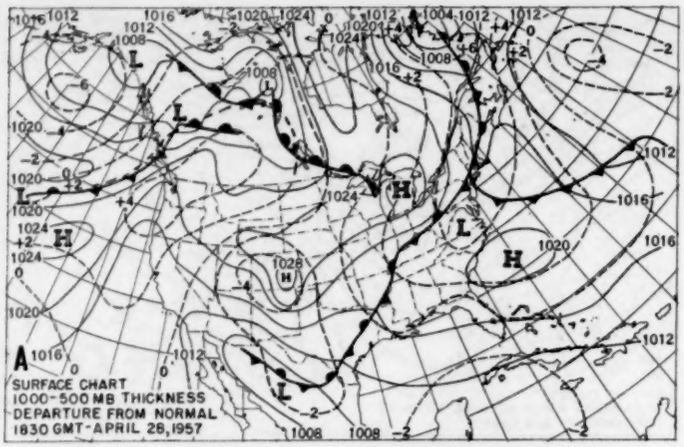
In the subsequent 24 hours the 500-mb. eastern ridge indicated definite displacement toward the Atlantic seaboard, while slight ridging appeared in the western sector of the long-wave trough over the Rocky Mountain States. At 1830 GMT April 27, the surface chart distinctly presented a changed pressure pattern. By then the moderate southerly flow of tropical maritime air had practically ceased over the eastern and east-central States. A moderate Pacific cold front had advanced eastward and extended from Detroit, Mich., southward through Springfield, Mo., to Laredo, Tex. High pressure centers over the East or along the eastern coastal waters had decreased in intensity and were separated by troughing. As these conditions developed over the eastern part of the country ridging intensified above the western States. The central portion of the ridge at this time extended from the coast of Washington and Oregon to eastern Nebraska. Two 1026-mb. high centers were located within this ridge.

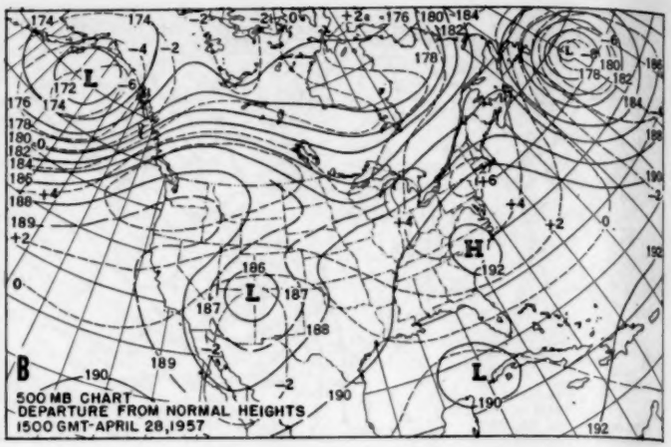
The closing stage of the heat wave is depicted by the charts in figure 3. These charts clearly define the advancing cold front, the loss of southerly flow, the weakening and broadening of the upper trough, and the eastward movement of the 500-mb. height changes and the 1000–500-mb. thickness changes. Thus, a return to more normal conditions and the death of a heat wave were indicated.

4. AREA AND INTENSITY OF HEAT WAVE

That this was a prolonged as well as a pronounced heat wave over the eastern States is indicated by a few facts and statements from the April Climatological Data. A study of these data revealed that between the 18th and 30th of the month the majority of eastern stations recorded average daily temperatures greater than the monthly normal. The area covered for 10 or more days with temperatures 6° F. or more above the monthly normal is outlined in figure 4. All of the region east of the Missouri and Mississippi Rivers, with the exception of Florida and portions of the coastal regions, was enclosed by this value. For increased anomaly values the size of the shaded areas decreases, the maximum value being reached in the Buffalo, N. Y., area on April 24 and 25 when maxima of 87° F., a deviation of 31° F. from the monthly normal on April 25, were recorded.

A few of the comments on the April Local Climatological Data forms from various stations might be of interest in relation to the warmth of the period. Akron, Ohio reported: "last 10 days of April produced average temperatures comparable to late June or early August." Cincinnati, Ohio: "Period of 19–27 was longest with maximum temperatures over 80° F. ever recorded in April." Lynchburg, Va.: "Heat wave 18–30 was longest to occur in April on record." Richmond, Va.: "The warm spell beginning on April 17 to the end of the month was the warm-





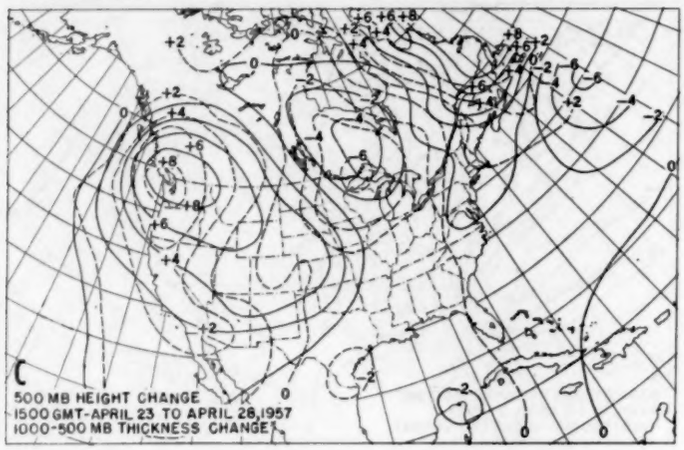


FIGURE 3.—(A) Sea level chart for 1830 GMT, and 1000–500-mb. departure from normal thickness pattern (dashed) for 1500 GMT, April 28, 1957. (B) 500-mb. contours and departure from-normal (dashed) for 1500 GMT, April 28, 1957. (C) 500-mb. 5-day height change and 1000–500-mb. 5-day thickness change chart (dashed) 1500 GMT April 23–28, 1957. Height values on all charts in hundreds of feet.

TABLE 1.—*Temperature records established or equaled, April 1957*

Station	April 1957								
	20	21	22	23	24	25	26	27	28
Hartford, Conn.		H							
Wilmington, Del.		H			T				
Washington, D. C.		H							R
Augusta, Ga.			T						
Louisville, Ky.	H								
Portland, Maine		R							
Baltimore, Md.		H							E
Boston, Mass.		H							
Nantucket, Mass.					H				
Alpena, Mich.	H								
East Lansing, Mich.	H								
Newark, N. J.		H			T				
Trenton, N. J.		H			H				
Buffalo, N. Y.	T		H		R	R		T	
Rochester, N. Y.					H				
Charlotte, N. C.		H	H						
Greensboro, N. C.		H			T				T
Wilmington, N. C.			R						
Sandusky, Ohio						H			
Erie, Pa.		T				H		R	R
Philadelphia, Pa.		H							H
Pittsburgh, Pa.								R	
Providence, R. I.		H							
Knoxville, Tenn.									H
Lynchburg, Va.		H							H
Richmond, Va.		H							H
Roanoke, Va.								R	
Huntington, W. Va.							E		
Parkersburg, W. Va.								H	
Schenectady, N. Y.				H	H				

H Highest for the date since records began.
T Tied highest for the date since records began.
R Highest for the month since records began.
E Equaled highest for the month since records began.

est in 60 years of record." Huntington, W. Va. reported: "The 11-day period 18–28, of 80° F. or above was the longest April warm spell of record." Thus, it appears that the conditions which produced this warm spell must have been unusual, at least for this season of the year.

Numerous records were established or equaled during this period of high temperatures over the East, as may be observed from table 1. It should be understood that this is not a complete summary of records that were equaled or established at the Weather Bureau first order stations during this period, but rather that it is a partial list from available records.

5. PERIODS OF MAXIMUM TEMPERATURES

A survey of the daily maxima at many of the United States and Canadian weather offices distinctly indicated an eastward or southeastward progression in the occurrence of high temperatures during this period under study. Results of this investigation also suggested that the appearance of the thermal climax was in intervals of from 3 to 5 days. Generally, in the northern and central sectors of the East there appeared three such periods.

The initial area of maximum temperatures began on April 18 as a narrow band extending from New Orleans to Wichita, thence to Bismarck, International Falls, and into Canada (fig. 5). Considerable expansion of area occurred on the 19th and by the 20th it enveloped the Great Lakes region and extended to Tennessee. By April 21 the zone of maximum temperatures during the 5-day period had swung to the east coast except for a small area in the Southeast. In this position it produced one of the warmest, and in some regions the hottest, Easter Sunday of record. By the 22d the wave of warm

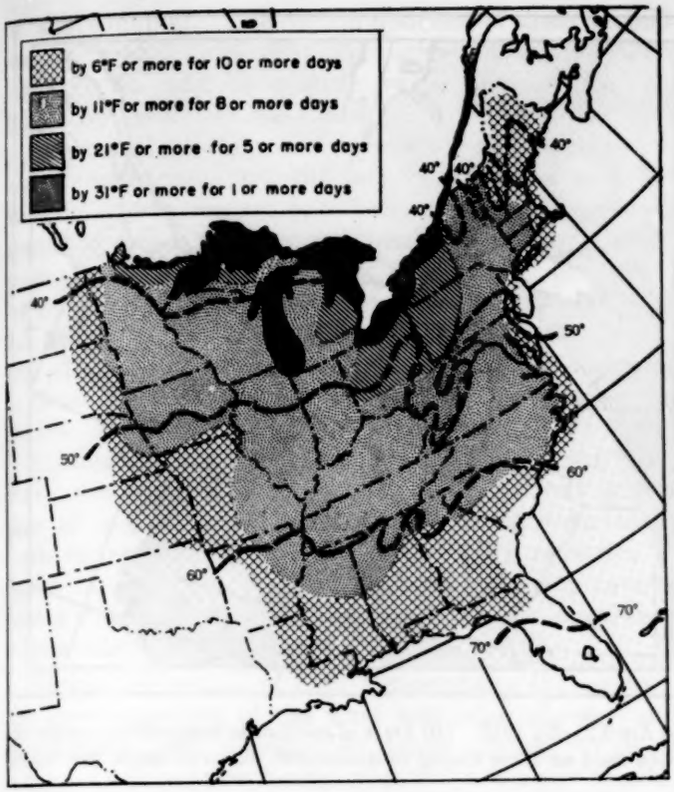

by 6°F or more for 10 or more days
by 11°F or more for 8 or more days
by 21°F or more for 5 or more days
by 31°F or more for 1 or more days

FIGURE 4.—The departure of the highest daily average temperature from the April monthly normal during the period April 18–30, 1957. Shading of different types has been used to distinguish different departure values (see legend on chart). Monthly mean isotherms for April are shown (dashed).

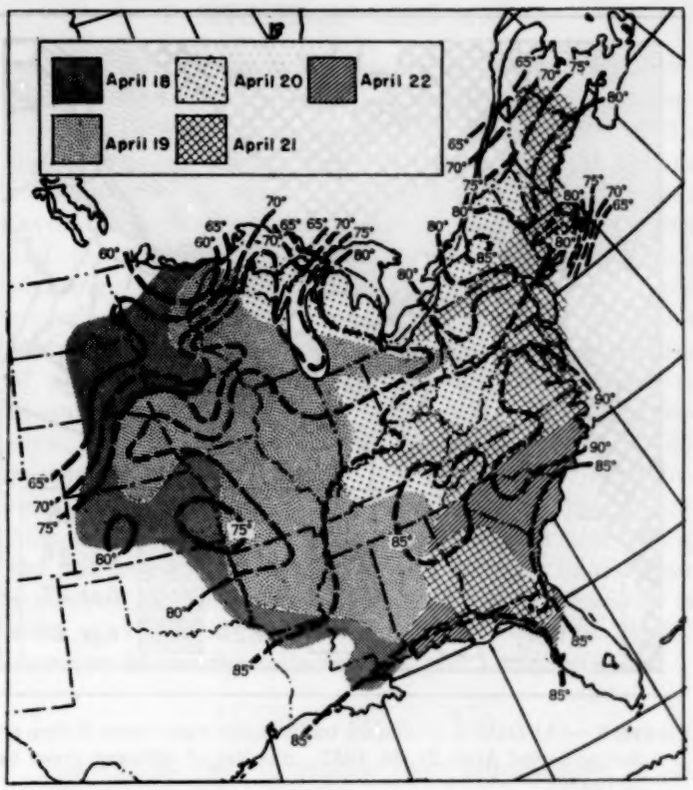


FIGURE 5.—Date of maximum temperature occurrence during period April 18–22, 1957. Shading of different types has been used to distinguish different dates (see legend on chart). Isotherms of maximum temperatures (dashed) during period April 18–22, 1957.

air had moved off the eastern seaboard except south of central Florida.

The second progression of high temperatures over the East reached its culmination prior to complete coverage of the eastern half of the Nation (fig. 6A). The initial impulse of high readings appeared on April 21 over the northern portion of the central and eastern Provinces of Canada and progressed south-southeastward until partial dissipation of the area of high temperatures appeared on the 24th; this region of high temperatures was practically eliminated from the chart on the 25th of April. Several possible reasons for this sudden cessation of the migration of these maximum temperatures are mentioned. It already has been stated that in the central portion of the East there was a prolonged period of high temperatures from the 18th to the 30th of April that set new records. Thus, it was difficult within this area to discern specific data for the appearance of a maximum, since readings frequently differed by only one or more degrees. Next, during the 23d and 24th considerable cloudiness prevailed over portions of Indiana, Ohio, New York, and Pennsylvania, with shower and thunderstorm activity during the afternoon hours. Finally, by midday of the 24th a "back-door" cold front had pushed southward over New England and eastern New York to bring cooling to that area.

The third invasion of high temperatures has been combined with the later stages of the second progression of high readings. Figure 6B contains the identical areas for the 24th and 25th as defined in figure 6A. These areas were repeated since temperature readings on these days were higher in the duplicated region than they were on the preceding or subsequent day. The areas of maximum temperatures in this final migration traversed the Nation in a more easterly direction and reached the coast on the 28th. Several new records were established during the latter period of this third migration of warm air.

Finally, it may be well to mention that the location of the 1000–700-mb. thickness warm tongue and the occurrence of maximum temperatures were prominently in close agreement on comparable dates. This area of daily highest temperature for a period was also in approximately similar agreement with the 1000–500-mb. thickness warm tongue and the 500-mb. constant pressure ridge line. However, the lower thickness chart indicated slightly closer agreement with the area of maximum temperatures. This is to be expected since the 1000–700-mb. thickness chart is a rather reasonable facsimile of the 850-mb.

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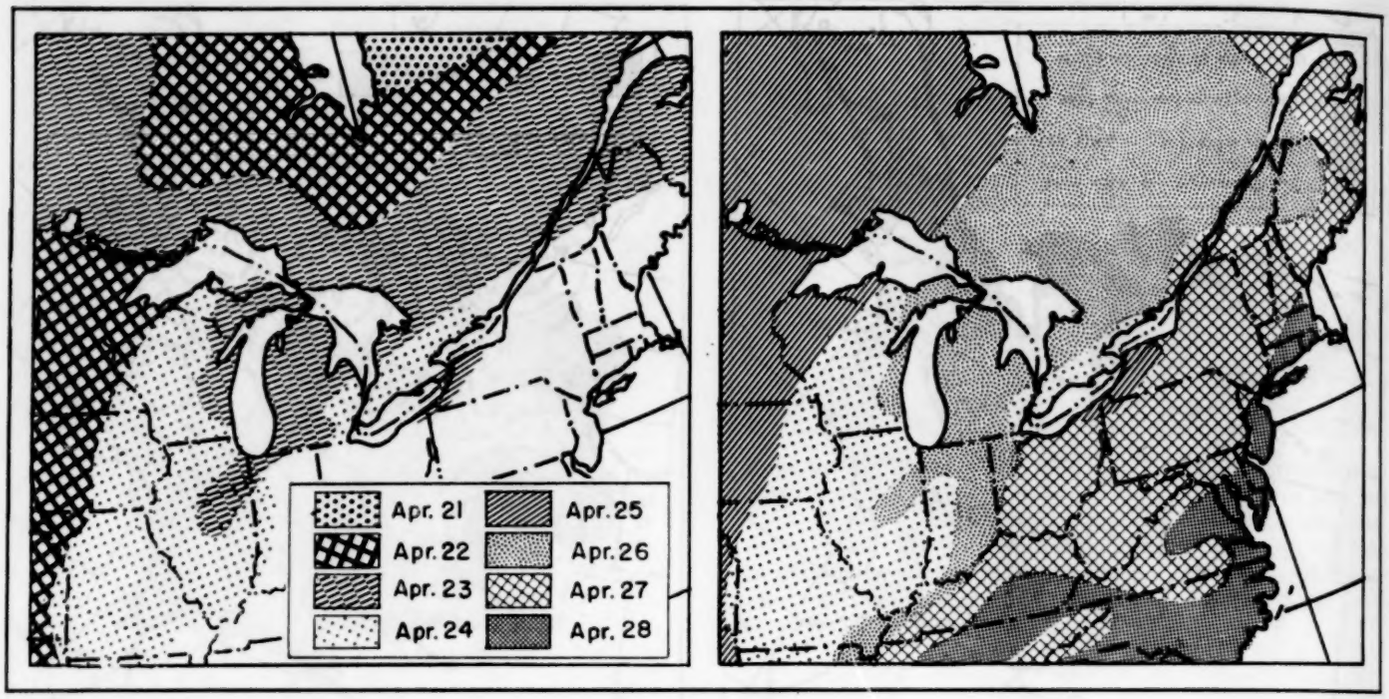

FIGURE 6.—(A) Date of maximum temperature occurrence during period April 21–25, 1957. (B) Date of maximum temperature occurrence during period April 24–28, 1957. Shading of different types has been used on these charts to distinugish different dates (see legend on chart).

temperature field, and this height normally is near the top of the afternoon dry adiabatic lapse rate in this area. Thus the use of thickness prognostic charts should aid considerably in locating the areas where temperatures will be the highest 24 to 48 hours hence.

6. FACTORS FAVORING HEAT WAVE

Some of the factors which occasioned this sudden and prolonged heat wave over the eastern States will be mentioned briefly in the following paragraphs.

Initially this change from subnormal to above normal temperatures over the eastern half of the country resulted from the readjustment in the planetary flow pattern over the Northern Hemisphere near the middle of April. This readjustment was attributed to the dissipation of one full-latitude trough over the Pacific Ocean as well as the development of a long-wave ridge over eastern Europe, thus producing subsequent displacements over the Northern Hemisphere of the long-wave troughs and ridges and their resultant locations over North America.

The mid-monthly adjustment in the planetary pattern over the Pacific produced a complete reversal in the position of the long-wave troughs and ridges over the United States. The long-wave trough above the eastern half of the country which had been productive of cold, wet weather during the first two weeks of April was almost instantaneously replaced by a long-wave ridge. (See Andrews [3] (fig. 1) for mean half-month 700-mb. charts for April.) For an illustration of the rapidity and magnitude of this pressure pattern adjustment note figure 1C where 500-mb. height and 1000–500-mb. thickness changes covering a 5-day period April 13–18 are presented. In the change charts immediately preceding or subsequent to this map the values were comparatively small.

The 5-day 500-mb. height change and the 1000–500-mb. thickness change for the period April 13–18 unmistakably defined this ridge as possessing warm characteristics. It will be noted that the thickness change comprised the greater portion of the 500-mb. height rise indicating that at sea level the pressure increase was only nominal. This fact may easily be observed by subtracting the 1000–500-mb. thickness values from the 500-mb. height values (fig. 1C) to obtain the 1000-mb. height change which may easily be converted into millibars. The resultant 1000-mb. chart would also show that the developing trough west of the ridge in this initial stage was associated principally with surface intensification.

Coincidental with these changes was the building of upstream and downstream blocks at both high and middle latitudes. Resultant intensification and sharpening of the amplitude in these troughs and ridges produced a more meridional flow over the Northern Hemisphere. One of the most pronounced areas of anticyclogenesis and blocking occurred over eastern Europe slightly prior to April 15. In this situation during one 24-hour period the 500-mb. height change chart indicated a rise of 1000 ft., and by April 21, the 500-mb. heights exceeded 1400

ft. above normal. The central positions of these anomalies migrated but slightly throughout the heat wave although the magnitude of the values decreased to near 700 ft. by the end of this study.

Because of blocking action and the development of strong meridional flow the large anticyclone over the eastern States remained practically stagnant for approximately 2 weeks, thus insuring persistence of the airmass over the area. Confirmation of this fact can be realized by reference to the cyclone and anticyclone tracks (Charts IX and X) or by observing figure 5B in Andrews' article [3]. These indicate that no cyclonic disturbance entered or developed in the eastern half of the Nation during this period.

Another feature that was compatible with this heat wave was the steady, prolonged, and relatively strong flow of tropical air northward. That this occurred at both surface and aloft is readily seen by reference to figure 2A–B. Thus, a source region of high temperatures and a means of transporting this warm air northward were available.

During this period of high temperatures the air over the greater portion of the East was relatively dry and precipitation was considerably below normal. This is not to say that some heavy rains did not occur locally, for they did, such as 1.24 inches in 20 minutes at Cincinnati, Ohio on the 22d. At Grand Rapids, Mich., heavy rain on April 24–25 flooded basements, streets, and viaducts. Rainfall for the last half of the month is shown in figure 4B and 4C of Andrews' article [3].

Thus, the following necessary ingredients for the development of a prolonged and pronounced heat wave were present: Stagnation of a large-amplitude anticyclone; height and thickness values considerably above normal at all levels; source region of tropical air and appropriate flow pattern for transportation of warm air over the region; little or no moisture in the upper air over the area, leaving the sky practically cloudless to allow maximum insolation; and finally, the lapse rate approaching the dry-adiabatic in the airmass to allow warming to a considerable depth.

7. EFFECTS OF HEAT WAVE

A few of the beneficial aspects as well as the detrimental effects that attended this hot period are mentioned. In many areas of the East the first half of the month was exceedingly wet and cold and so the change to a hot and comparatively precipitation-free regime was favorable to farming communities. It permitted drying and the working of the soil in preparation for spring planting. The sunshine aided materially in the rapid growth of many early crops. However, on the debit side there were areas in New England where a paucity of precipitation had existed for some time. Here, in conjunction with the lack of moisture, high temperatures, and at times strong to locally gale force winds, pastures and forests reached tinder dryness. Fires became numerous and forests were closed to the public. Massachusetts alone reported over 100 forest fires during the last half of the month. Many summer homes were destroyed by fire in New Hampshire, and thousands of acres of woodland were burned in the States of Massachusetts, Maine, New Hampshire, and Vermont.

ACKNOWLEDGMENTS

The writers wish to express their appreciation to the staff members of NAWAC for helpful suggestions and the reviewing of the article; to the Daily Map Unit of the Weather Bureau for detailed drafting of the figures.

REFERENCES

1. U. S. Weather Bureau, *Weekly Weather and Crop Bulletin, National Summary*, vol. XLIV, No. 18, May 6, 1957, Chart C, p. 4.
2. U. S. Weather Bureau, *Weekly Weather and Crop Bulletin, National Summary*, vol. XLIV, No. 14, Apr. 8, 1957, and No. 15, Apr. 15, 1957, Chart A, p. 3.
3. J. F. Andrews, "The Weather and Circulation of April 1957—A Stormy Month Over the United States Characterized by Two Contrasting Temperature Regimes," *Monthly Weather Review*, vol. 85, No. 4, Apr. 1957, pp. 124–131.

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Articles are accepted for the *Monthly Weather Review* with the understanding that they have not been published or accepted for publication elsewhere.

Two copies of the *manuscript* should be submitted. All copy, including footnotes, references, tables, and legends for figures should be double spaced with margins of at least 1 inch on sides, top, and bottom. Some inked corrections are acceptable but pages with major changes should be retyped. The style of capitalization, abbreviation, etc., used in the *Review* is governed by the rules set down in the Government Printing Office Style Manual.

Tables should be typed each on a separate page, with a title provided. They should be numbered consecutively in arabic numerals.

In *equations* conventional symbols in accordance with the American Standards Association Letter Symbols for Meteorology should be used. If equations are written into the manuscript in longhand, dubious-looking symbols should be identified with a penciled note.

References should be listed on a separate sheet and numbered in the order in which they occur in the text; or, if there are more than 10, in alphabetical order according to author. The listing should include author, title, source (if a magazine the volume, number, month, year, and complete page numbers; if a book the publisher, place of publication, date, and page numbers). If reference is made to a self-contained publication, the author, title, publisher, place of publication, and date should be given. Within the text references should be indicated by Arabic numbers in brackets to correspond to the numbered list.

Footnotes should be numbered consecutively in Arabic numerals and indicated in the text by superscripts. Each should be typed at the bottom of the page on which the footnote reference occurs.

Illustrations. A list of legends for the illustrations should be typed (double spaced) on a separate sheet. Each illustration should be numbered in the margin or on the back outside the image area. To fit into the *Review* page, illustrations must take a reduction not to exceed 3½″ x 9″ (column size) or 7½″ x 9″ (page size). Map bases should show only political and continental boundaries and latitude and longitude lines, unless data are to be plotted, when station circles will also be needed. Usually the less unnecessary detail in the background the better will be the result from the standpoint of clear reproduction. Line drawings and graphs should also be uncluttered with fine background grids unless the graph demands very close reading. It is not necessary to submit finished drawings, as drafting work can be done at the time the paper is prepared for publication.

Photographs should be sharp and clear, with a glossy surface. Bear in mind that marks from paper clips or writing across the back will show up in the reproduction. Drawings and photographs should be protected with cardboard in mailing.

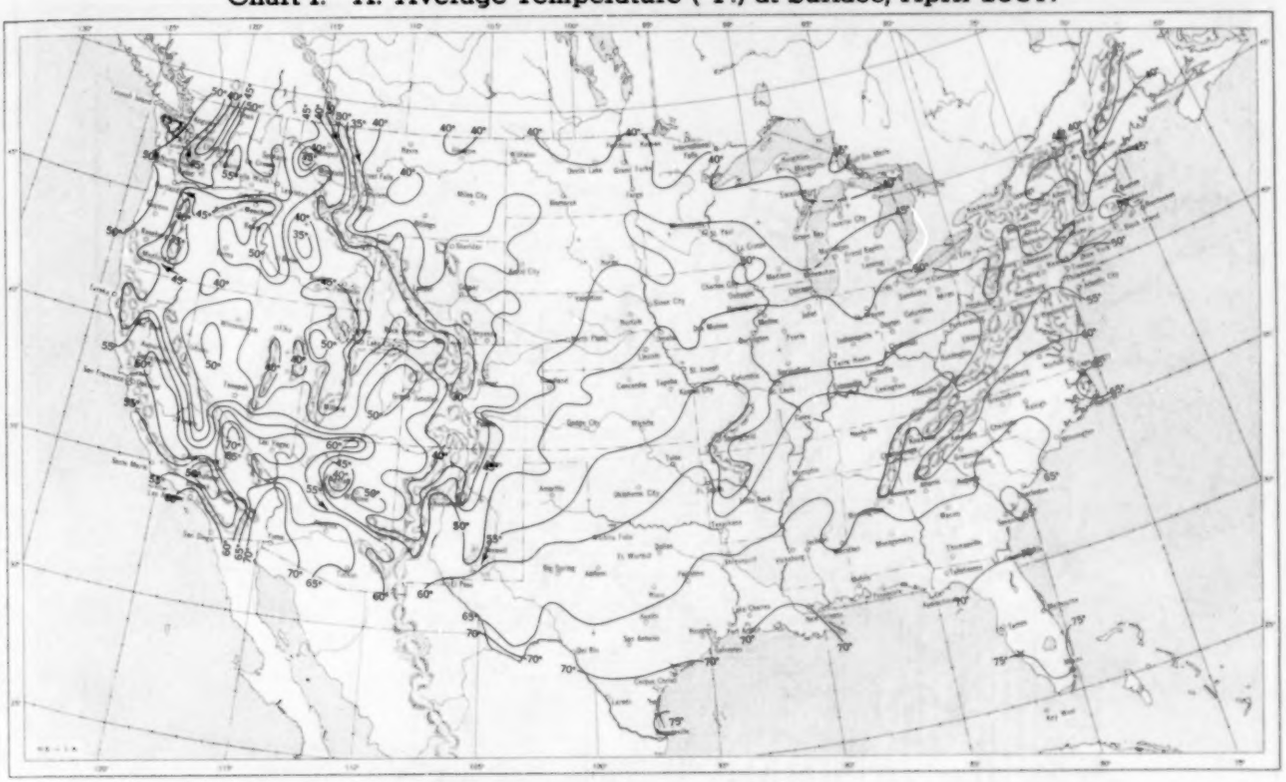
Weather Notes

Many years ago the *Monthly Weather Review* published detailed eye-witness accounts of exceptional storms. These accounts both enrich the meteorologist's knowledge of storms and provide him with particular details that cannot be found elsewhere. Because such information bears directly upon questions the meteorologists must attempt to answer about weather phenomena (for example, the identification of storms as tornadoes), and because the information has potential value in both the research and service programs of the Weather Bureau, publication of eye-witness accounts of exceptional storms and other meteorological phenomena was resumed in the April 1955 issue. They appear from time to time under the heading "Weather Notes."

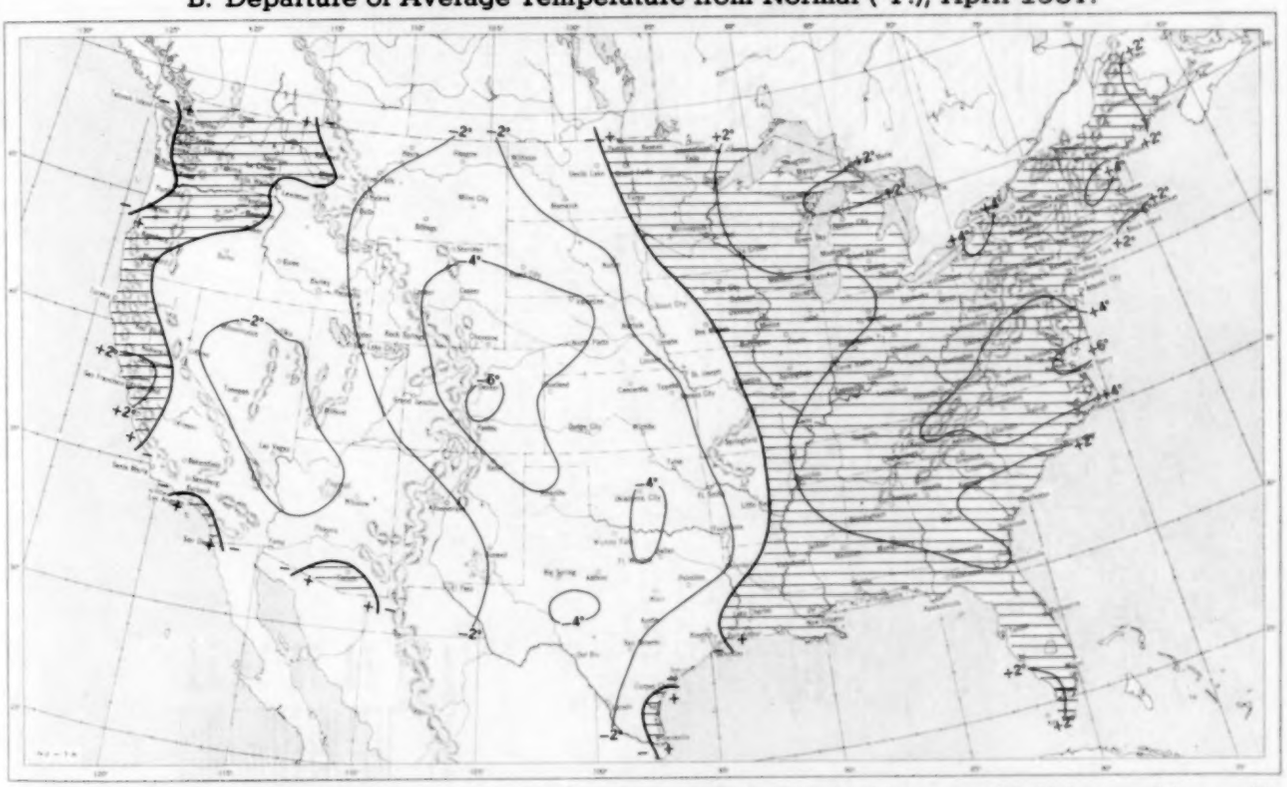
Contributions to these "Notes" are invited from readers of the Review. There is no limitation placed on length of description but it is expected that most will be short accounts. Any weather pecularities, whether storms or other phenomena, are acceptable subject matter. Material should be addressed to Editor, Monthly Weather Review, U. S. Weather Bureau, Washington 25, D. C.

U. S. GOVERNMENT PRINTING OFFICE: 1957

Chart I. A. Average Temperature (°F.) at Surface, April 1957.



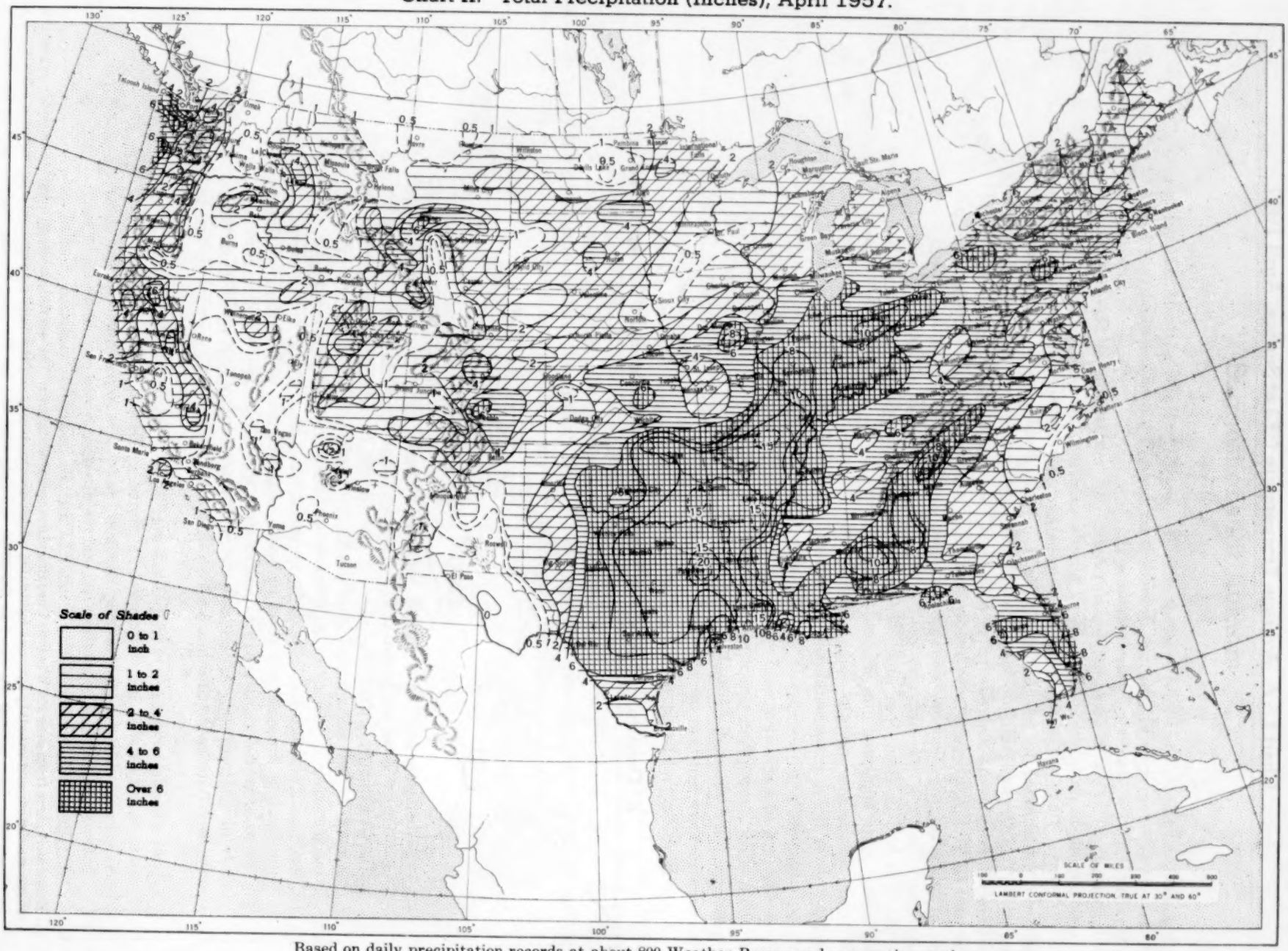
B. Departure of Average Temperature from Normal (°F.), April 1957.



A. Based on reports from over 900 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.

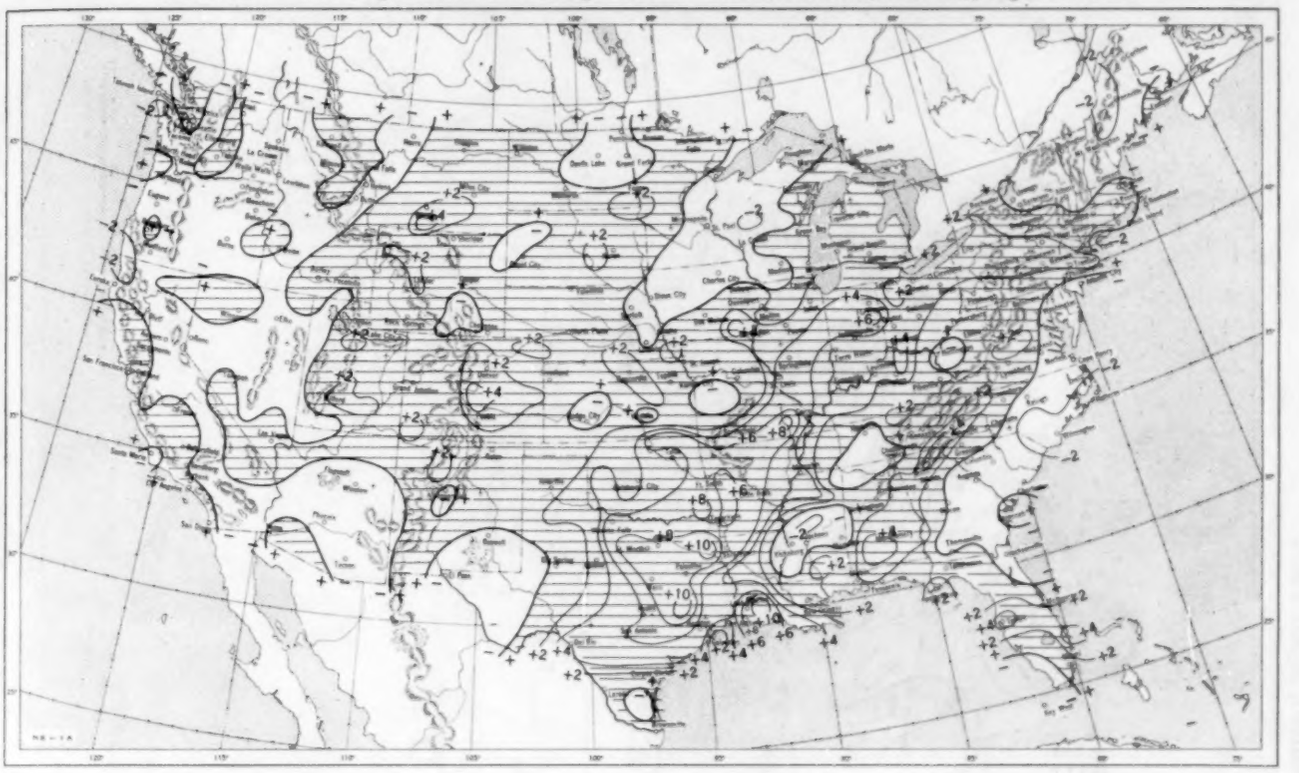
B. Departures from normal are based on the 30-yr. normals (1921-50) for Weather Bureau stations and on means of 25 years or more (mostly 1931-55) for cooperative stations.

Chart II. Total Precipitation (Inches), April 1957.

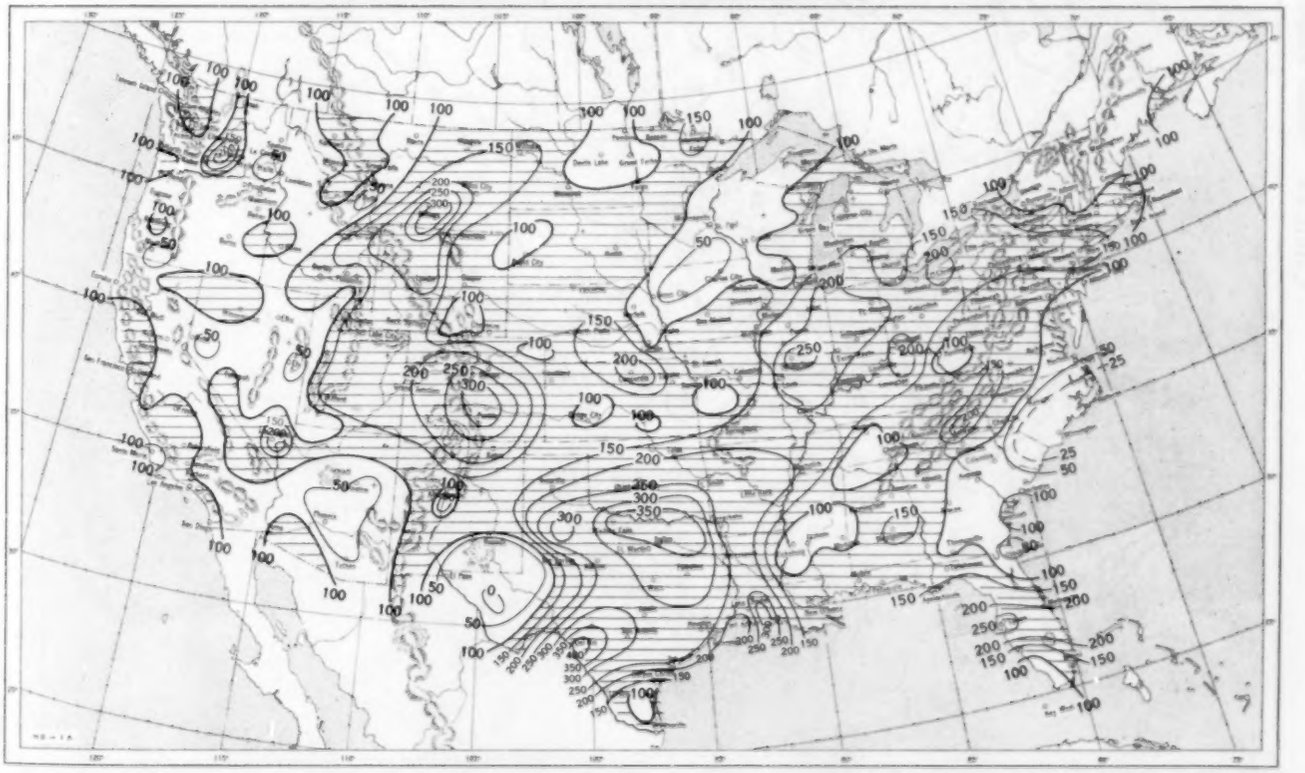

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION, TRUE AT 30° AND 60°

Based on daily precipitation records at about 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), April 1957.

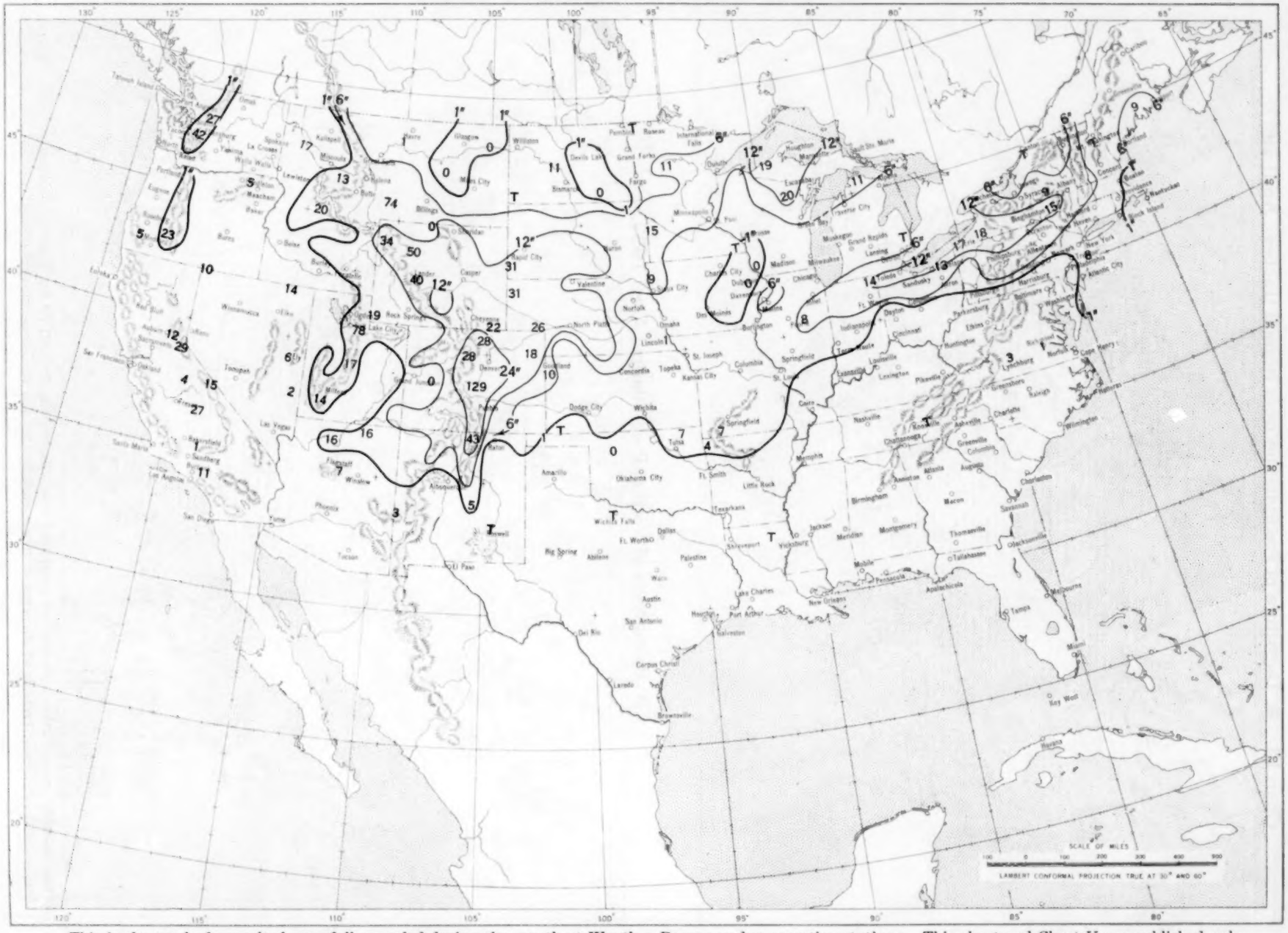


B. Percentage of Normal Precipitation, April 1957.



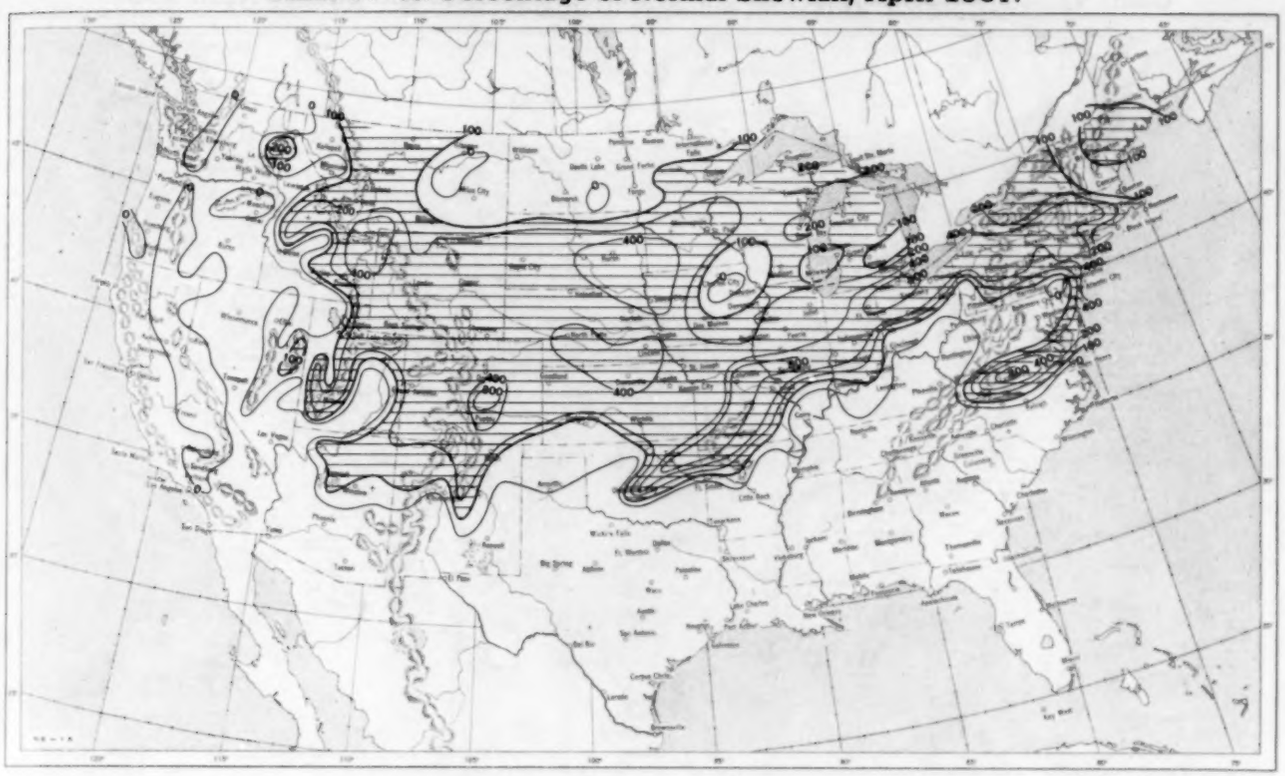
Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

Chart IV. Total Snowfall (Inches), April 1957.



This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

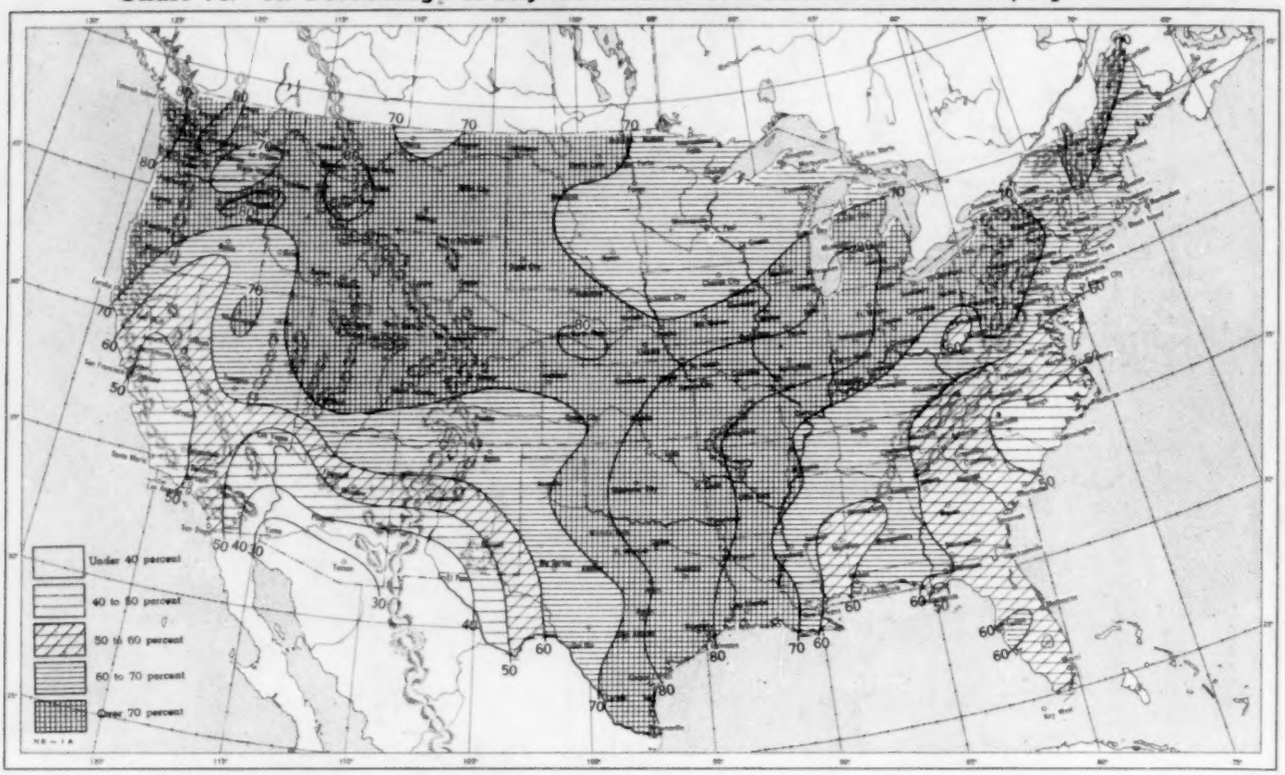
Chart V. A. Percentage of Normal Snowfall, April 1957.



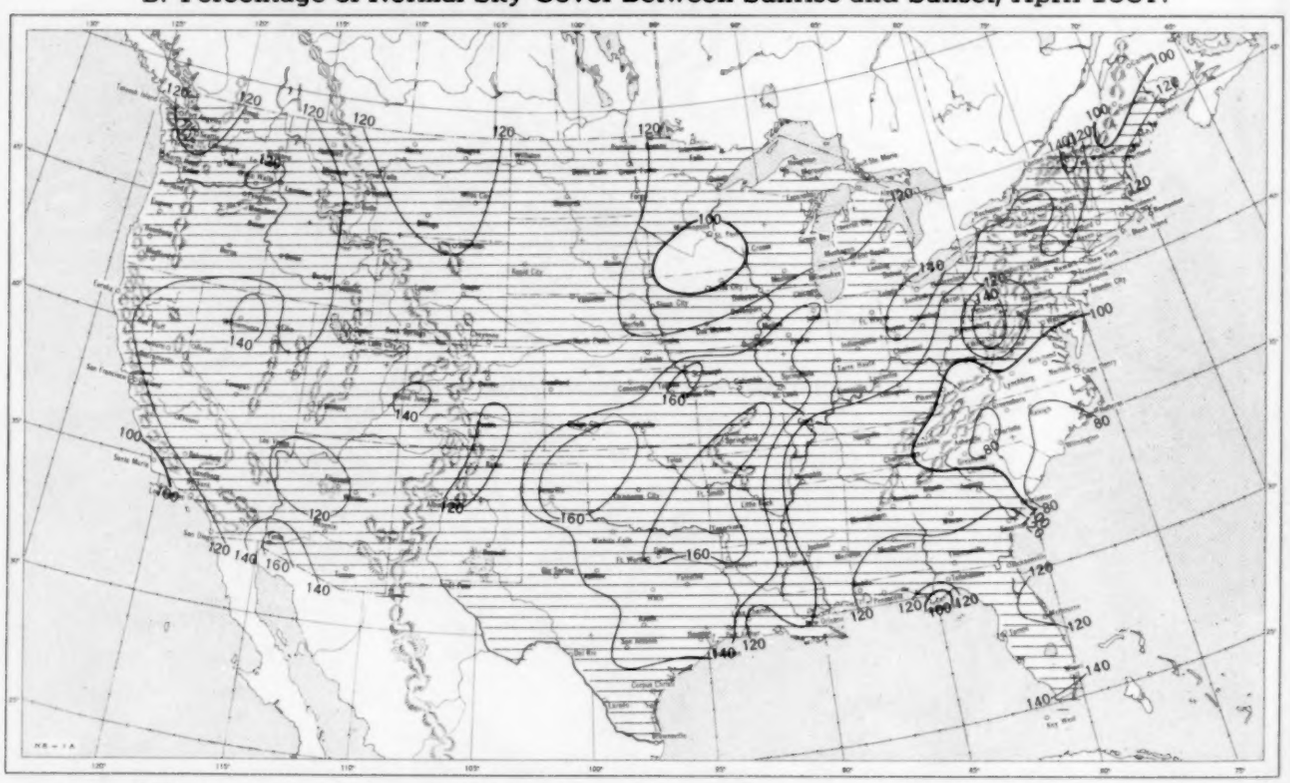
B. Depth of Snow on Ground (Inches). 7:30 a. m. E. S. T., April 29, 1957.

A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E. S. T., of the Monday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, April 1957.

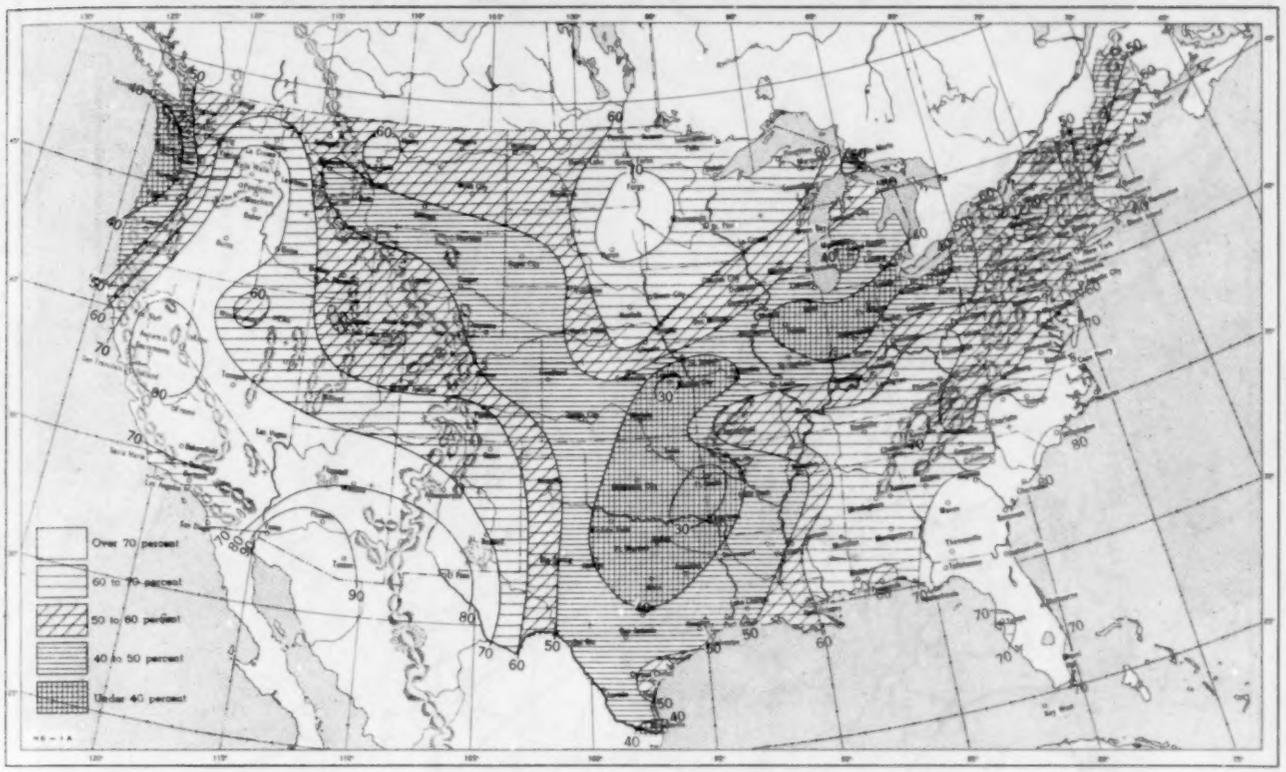


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, April 1957.

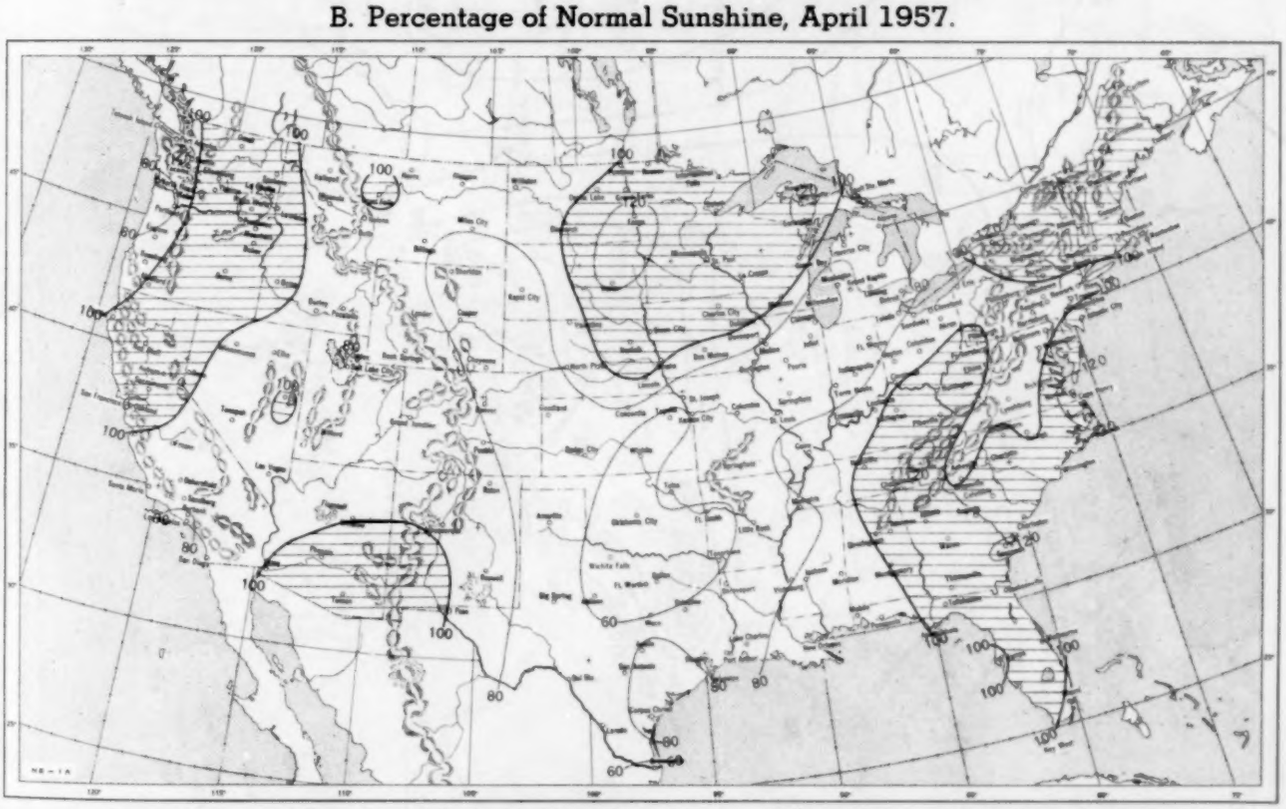


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, April 1957.



B. Percentage of Normal Sunshine, April 1957.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, April 1957. Inset: Percentage of Mean Daily Solar Radiation, April 1957. (Mean based on period 1951-55.)

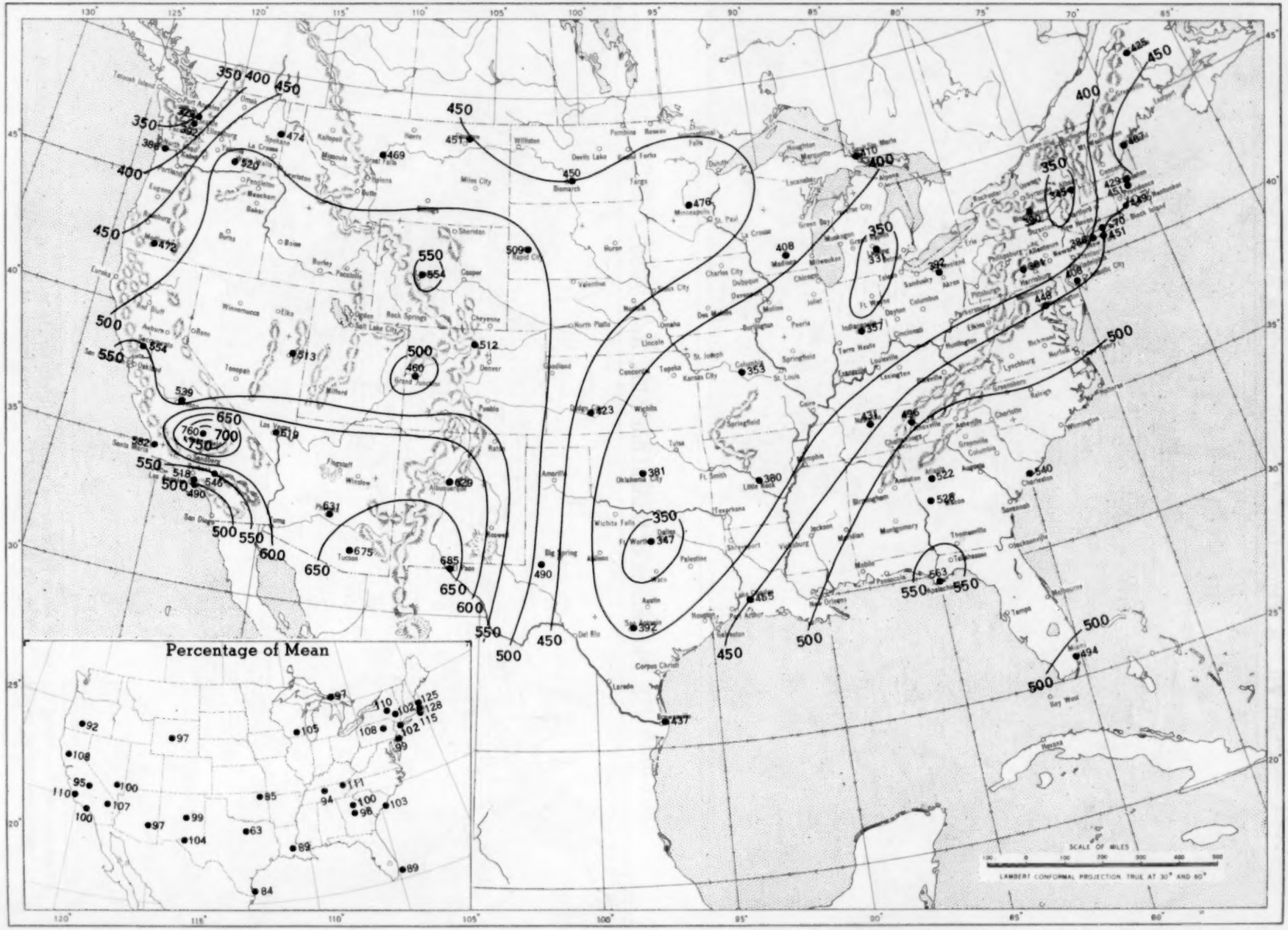
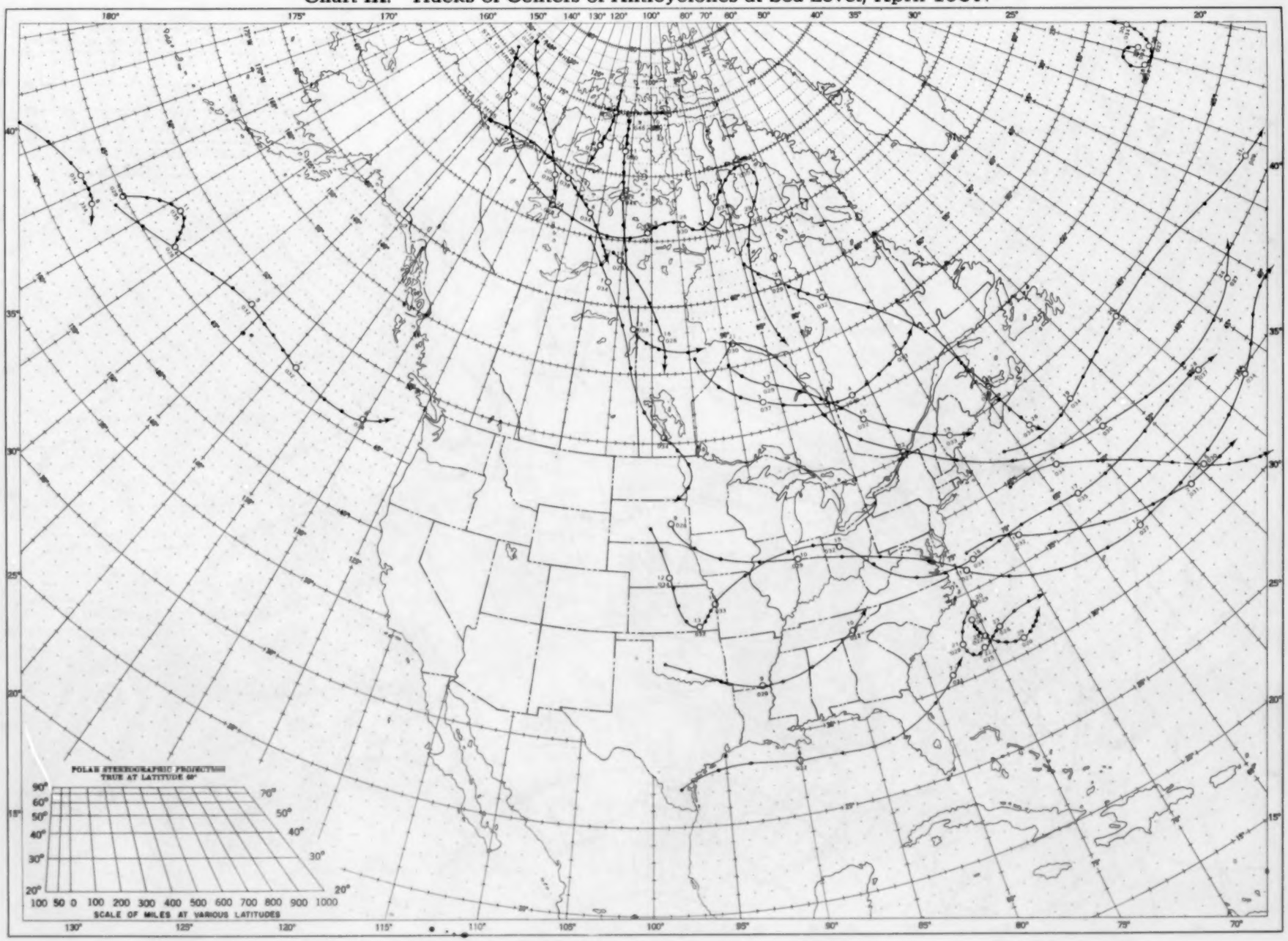


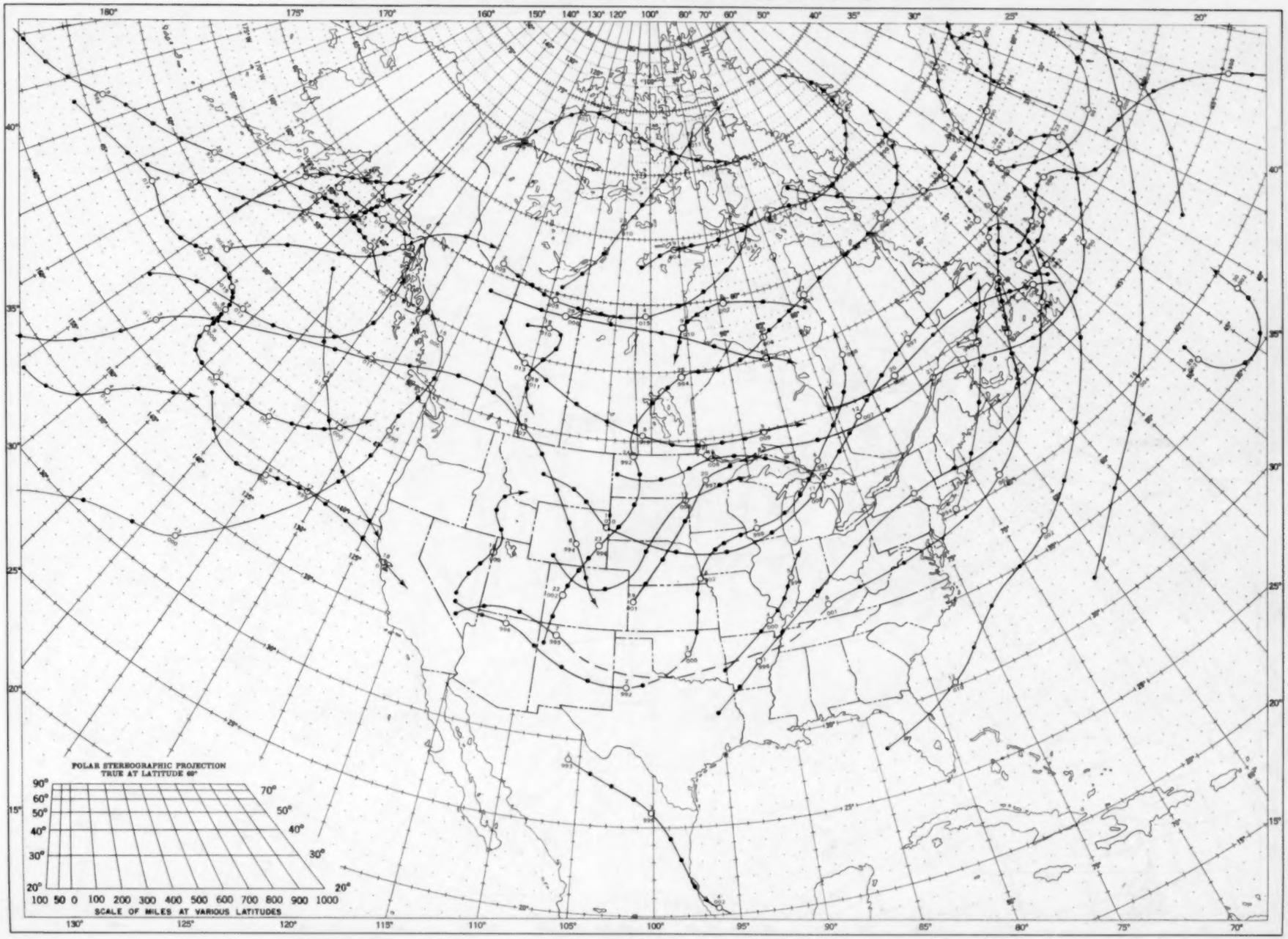
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. The inset shows the percentage of the mean based on the period 1951-55.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, April 1957.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

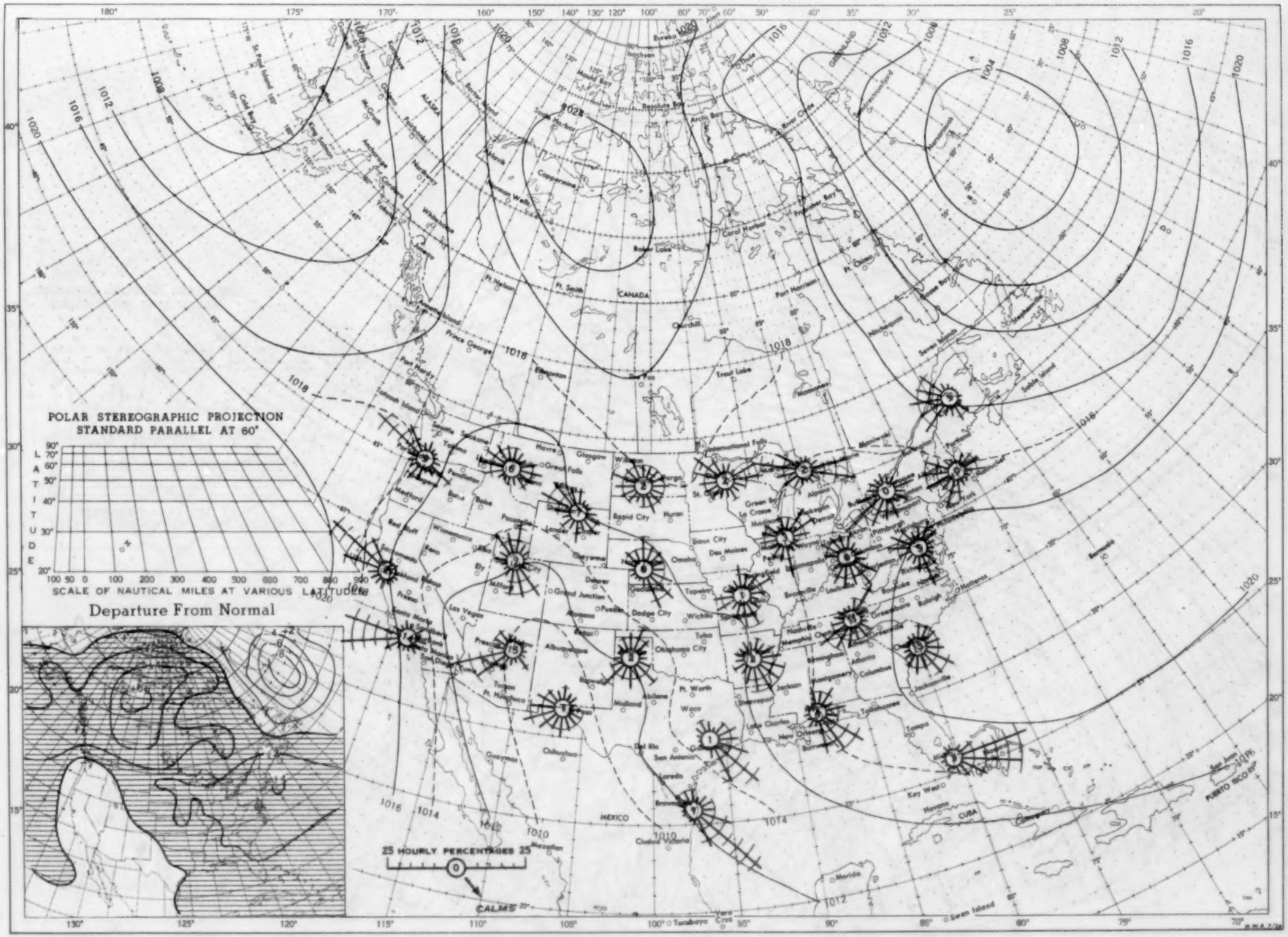
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, April 1957.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

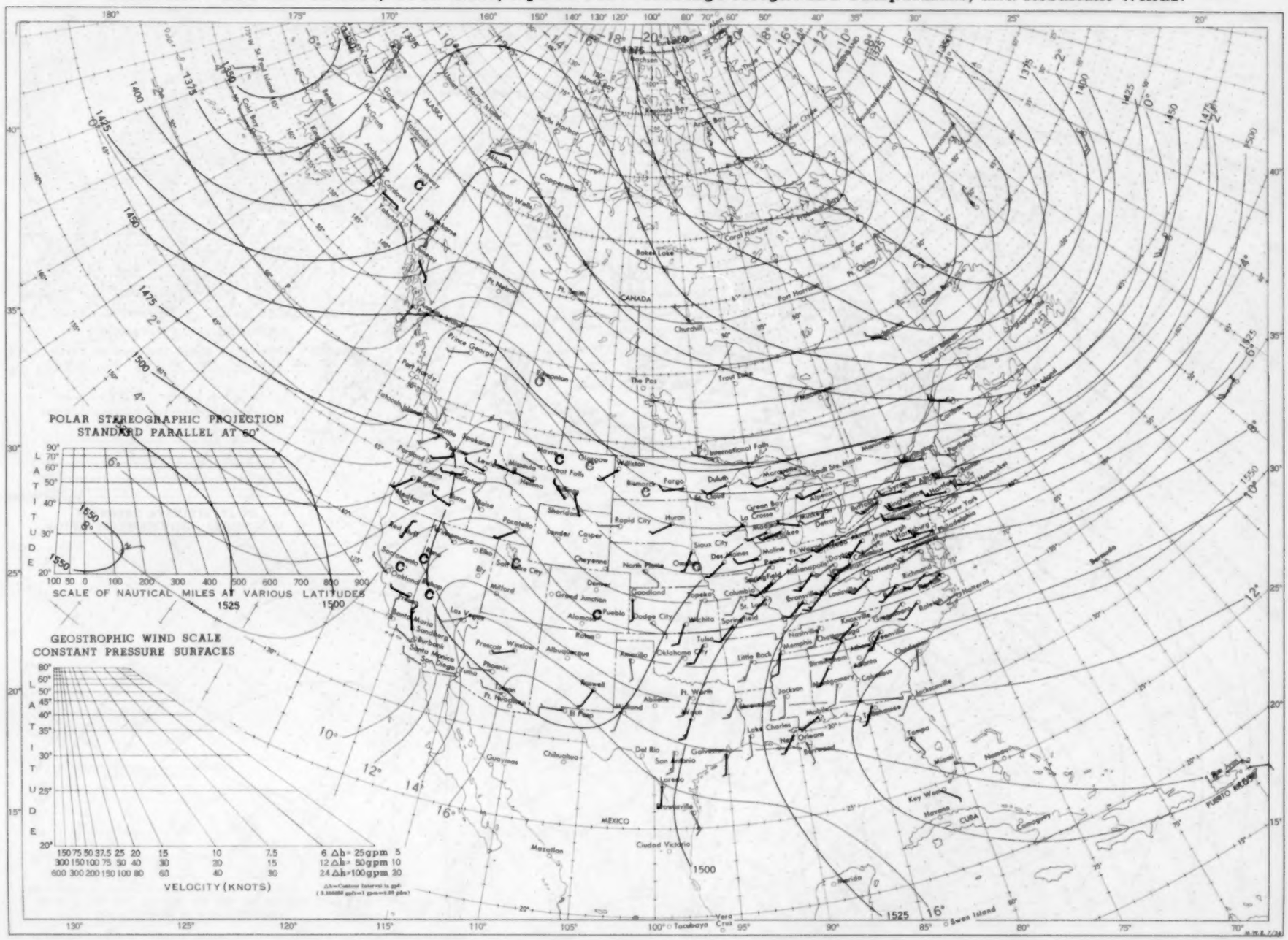
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, April 1957. Inset: Departure of Average Pressure (mb.) from Normal, April 1957.



Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

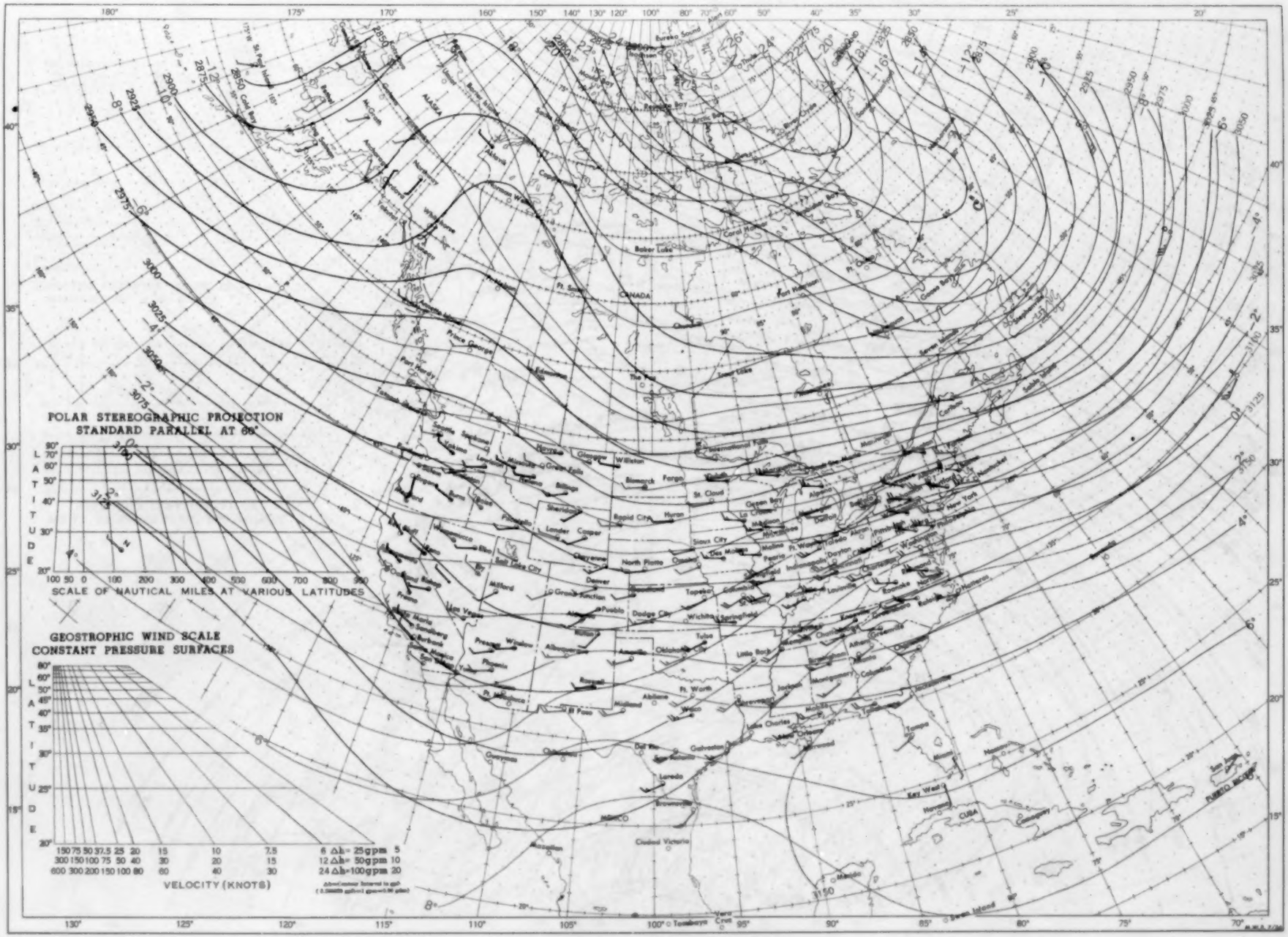
Chart XII. 850-mb. Surface, 0300 GMT, April 1957. Average Height and Temperature, and Resultant Winds.



Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. Winds shown in red are based on rawins taken at the indicated pressure surface and time. Those in black are based on pibals taken at 2100 GMT and are for the nearest standard height level.

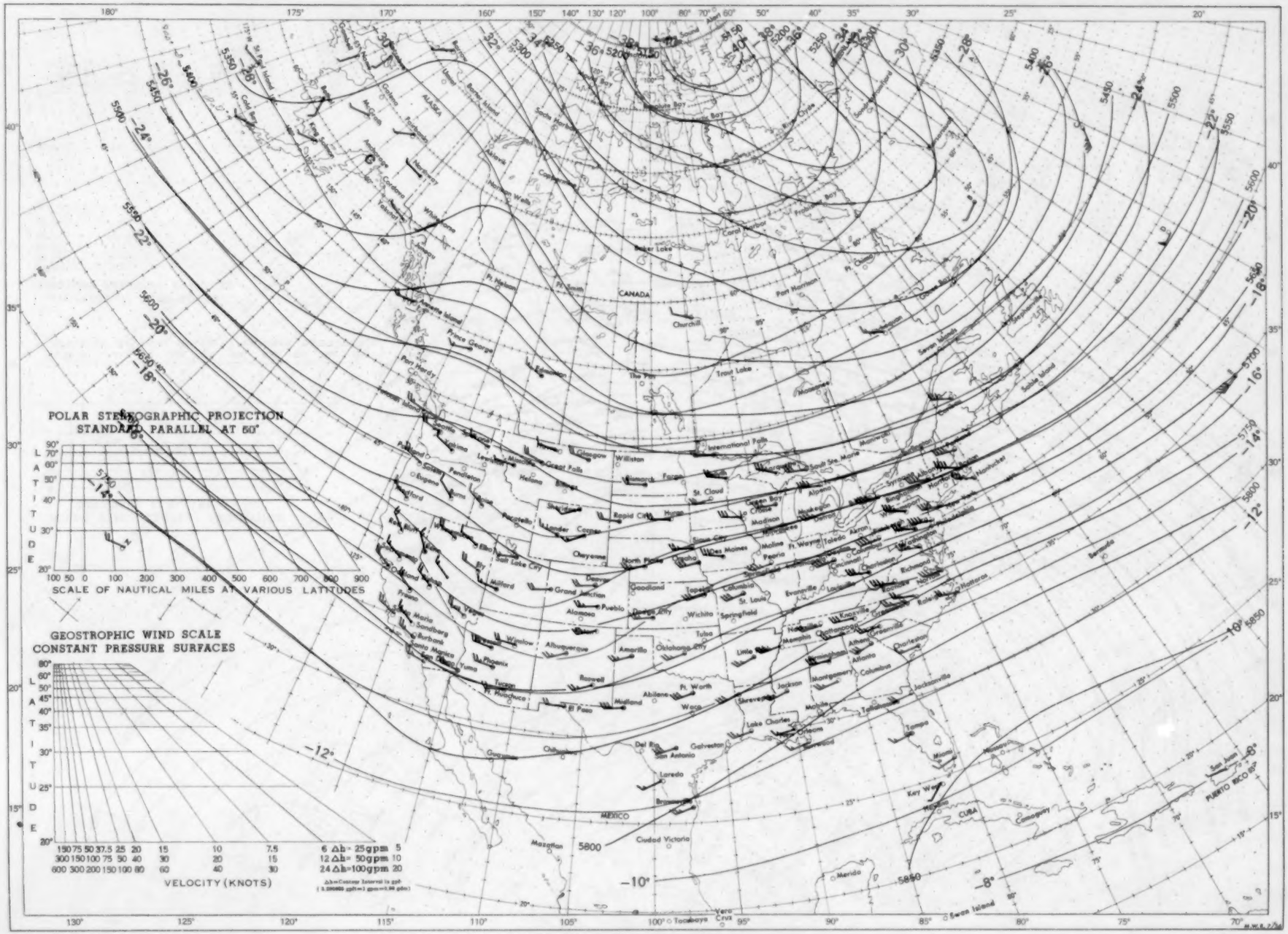
on pibals taken at 2100 GMT and are for the nearest standard height level.

Chart XIII. 700-mb. Surface, 0300 GMT, April 1957. Average Height and Temperature, and Resultant Winds.



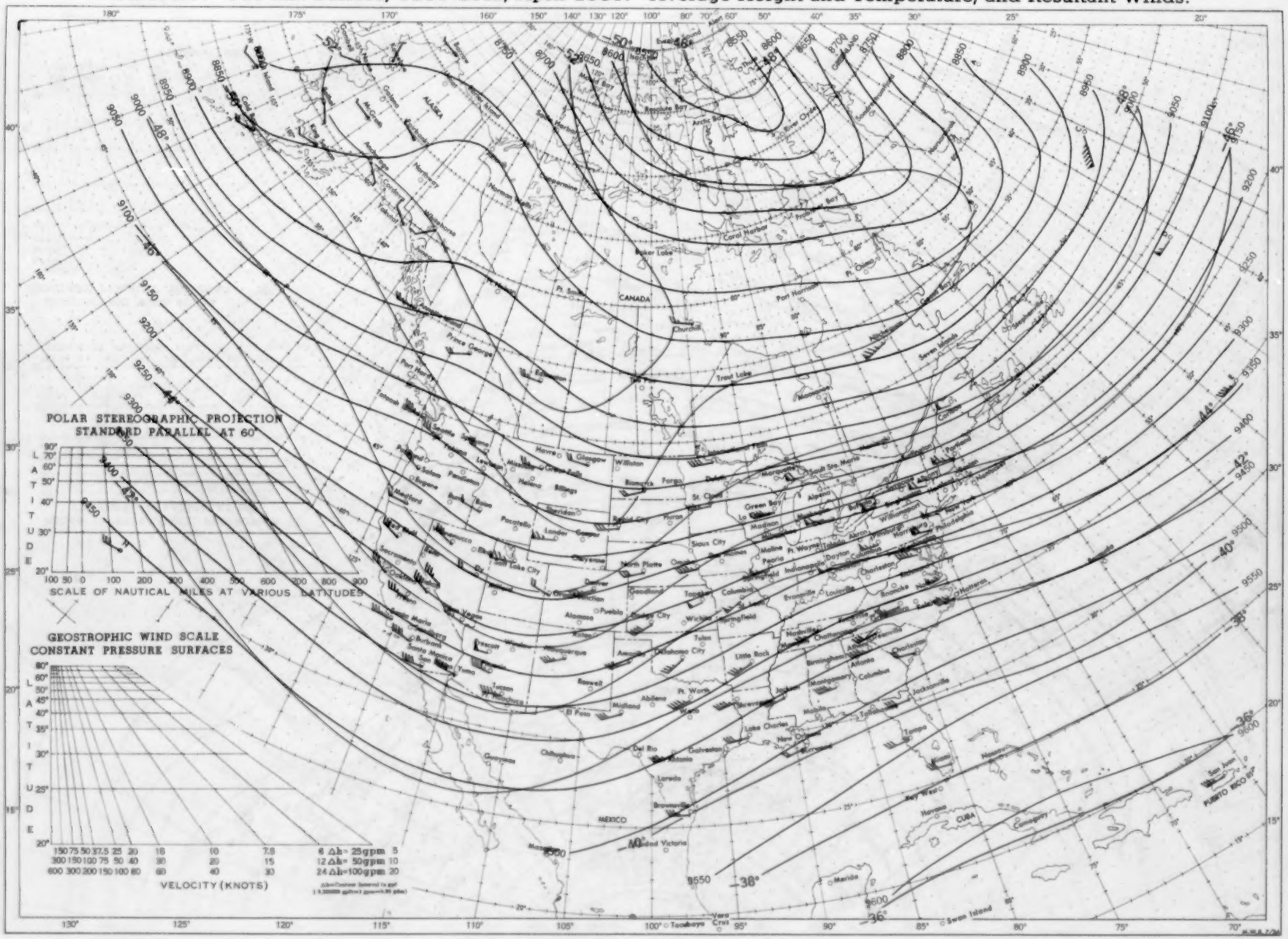
See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 0300 GMT, April 1957. Average Height and Temperature, and Resultant Winds.



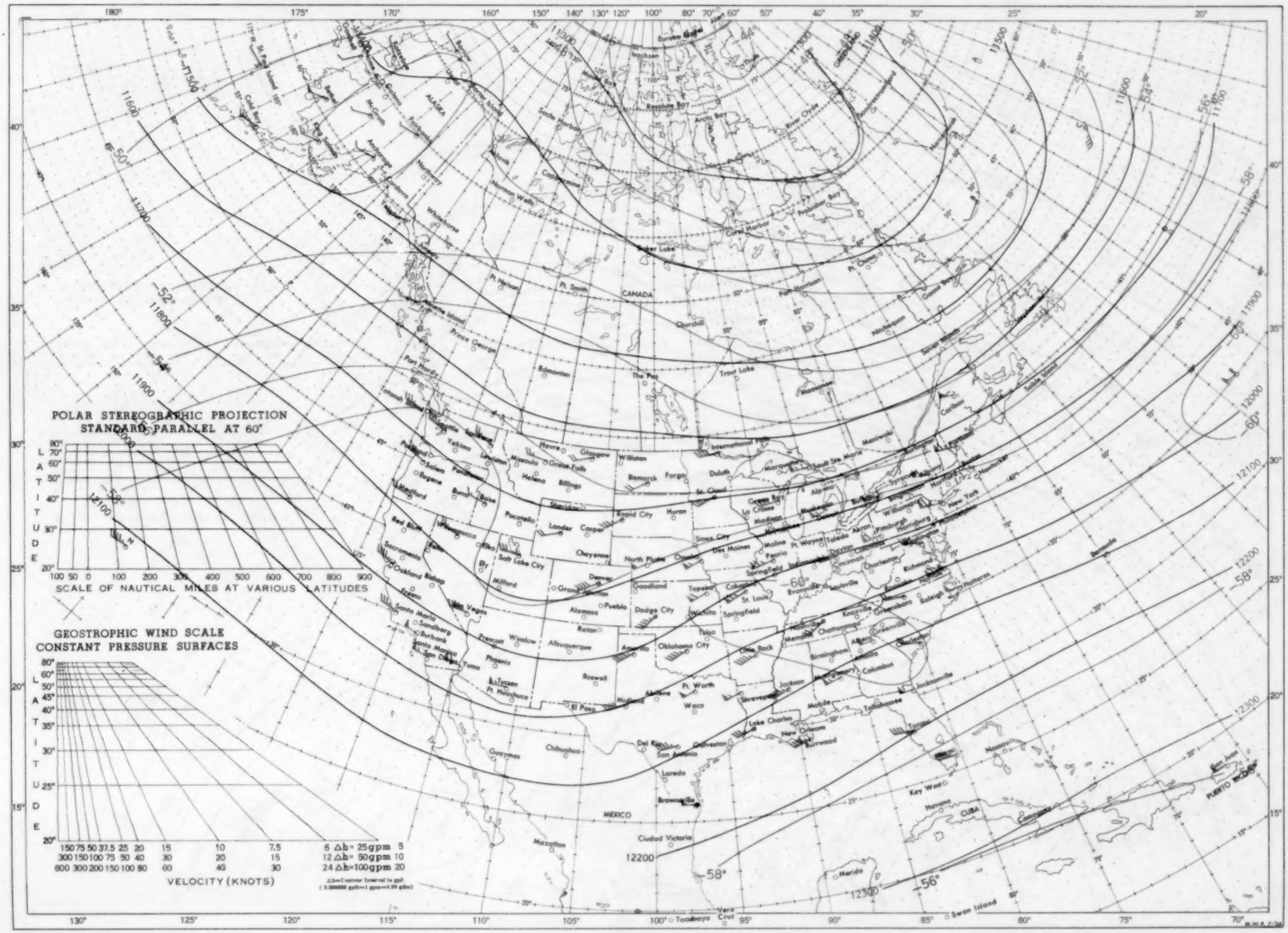
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 0300 GMT, April 1957. Average Height and Temperature, and Resultant Winds.



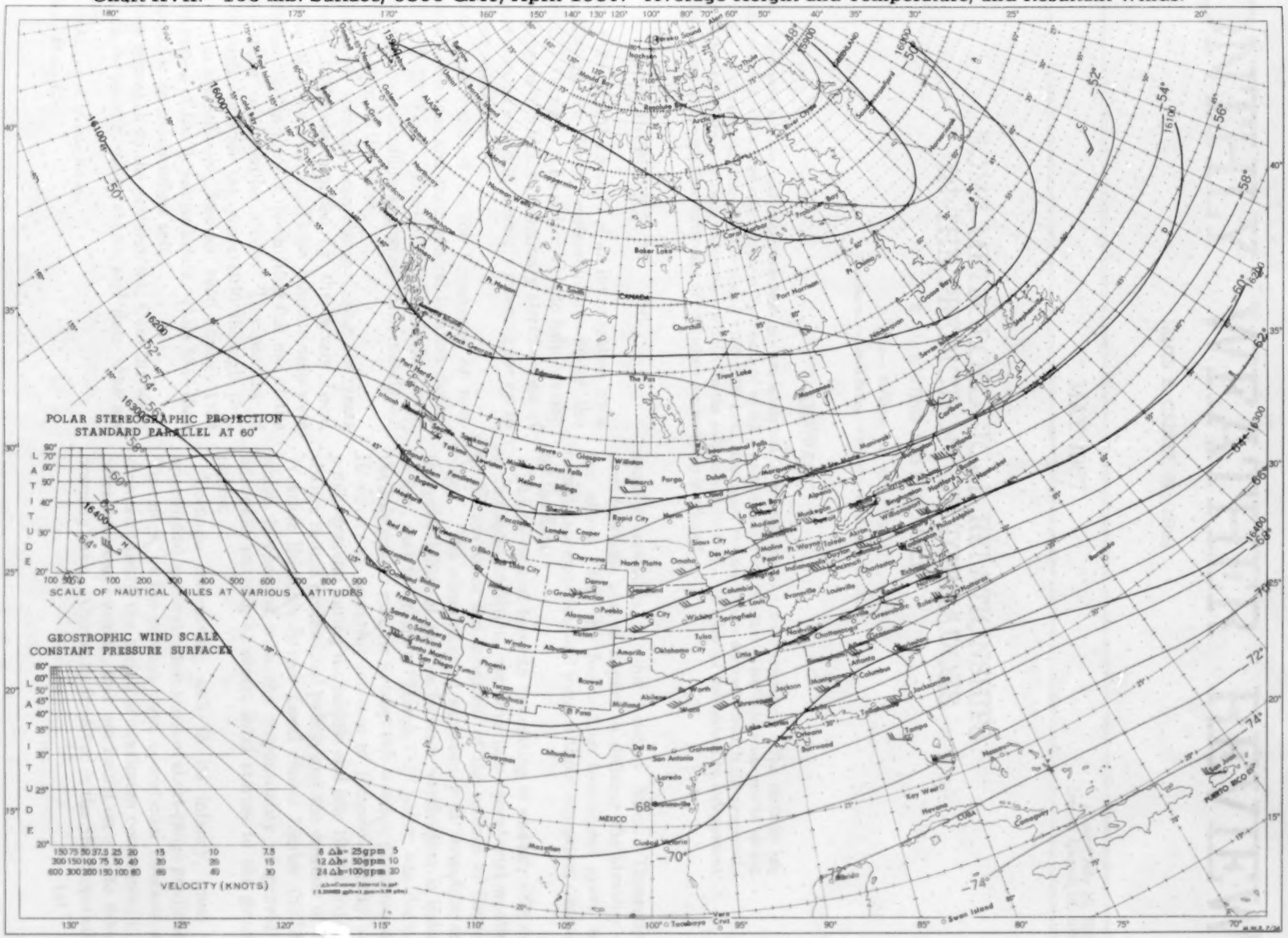
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 0300 GMT, April 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map. All winds are from rawin reports.

Chart XVII. 100-mb. Surface, 0300 GMT, April 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map. All winds are from rawin reports.